LONGITUDINAL STABILITY AND CONTROL DERIVATIVES OF A JET FIGHTER AIRPLANE EXTRACTED FROM FLIGHT TEST DATA BY UTILIZING MAXIMUM LIKELIHOOD ESTIMATION

*by George G. Steinmetz, Russell V. Parrish,
and Roland L. Bowles*

*Langley Research Center
Hampton, Va. 23365*

1. Report No. NASA TN D-6532	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle LONGITUDINAL STABILITY AND CONTROL DERIVATIVES OF A JET FIGHTER AIRPLANE EXTRACTED FROM FLIGHT TEST DATA BY UTILIZING MAXIMUM LIKELIHOOD ESTIMATION		5. Report Date March 1972
		6. Performing Organization Code
7. Author(s) George G. Steinmetz, Russell V. Parrish, and Roland L. Bowles		8. Performing Organization Report No. L-7882
9. Performing Organization Name and Address .NASA Langley Research Center Hampton, Va. 23365		10. Work Unit No. 136-62-01-03
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A method of parameter extraction for stability and control derivatives of aircraft from flight test data, implementing maximum likelihood estimation, has been developed and successfully applied to actual longitudinal flight test data from a modern sophisticated jet fighter. The results of this application establish the merits of the estimation technique and its computer implementation (allowing full analyst interaction with the program) as well as provide data for the validation of a portion of the Langley differential maneuvering simulator (DMS). The results are presented for all flight test runs in tabular form and as time history comparisons between the estimated states and the actual flight test data. Comparisons between extracted and manufacturer's values for five major derivatives are presented and reveal good agreement for these principal derivatives with the exception of the static longitudinal stability derivative C_{m_α}. This particular derivative is extensively investigated by utilizing the interactive capabilities of the computer program. The results of this investigation verify the numbers extracted by maximum likelihood estimation.

17. Key Words (Suggested by Author(s)) Parameter estimation Maximum likelihood Longitudinal stability and control characteristics		18. Distribution Statement Unclassified — Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified		21. No. of Pages 43	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

LONGITUDINAL STABILITY AND CONTROL DERIVATIVES

OF A JET FIGHTER AIRPLANE EXTRACTED FROM FLIGHT TEST DATA

BY UTILIZING MAXIMUM LIKELIHOOD ESTIMATION

By George G. Steinmetz, Russell V. Parrish,
and Roland L. Bowles
Langley Research Center

SUMMARY

A method of parameter extraction for stability and control derivatives of aircraft from flight test data, implementing maximum likelihood estimation, has been developed and successfully applied to actual longitudinal flight test data from a modern sophisticated jet fighter. The results of this application establish the merits of the estimation technique and its computer implementation (allowing full analyst interaction with the program) as well as provide data for the validation of a portion of the Langley differential maneuvering simulator (DMS). The results are presented for all flight test runs in tabular form and as time history comparisons between the estimated states and the actual flight test data. Comparisons between extracted and manufacturer's values for five major derivatives are presented and reveal good agreement for these principal derivatives with the exception of the static longitudinal stability derivative C_{m_α}. This particular derivative is extensively investigated by utilizing the interactive capabilities of the computer program. The results of this investigation verify the numbers extracted by maximum likelihood estimation.

INTRODUCTION

A method of parameter extraction for stability and control derivatives of aircraft from flight test data has been developed at the Langley Research Center (ref. 1). This method utilizes maximum likelihood estimation, an advanced mathematical theory, and has been fully implemented on the Langley Research Center real-time digital complex (ref. 2). The casting of the digital program in such a framework permits the analyst to interact with the program through a control console and cathode ray display.

Applying the computer program to actual flight test data from a modern sophisticated jet fighter airplane (fig. 1) serves a dual purpose: first, to establish the merits of the computer program and, second, to provide additional means of validating the Langley

differential maneuvering simulator (DMS) program (ref. 3). The successful extraction of stability derivatives from real-world flight test data goes a step beyond the use of analytically generated data toward establishing the creditability and merits of any estimation technique. The documentation of the aerodynamic characteristics of the test airplane (ref. 4) is extensive and is currently being used as a prime source for the DMS program package. The DMS provides dual-cockpit fixed-base simulation in which the two piloted vehicles can be operated jointly or individually in either a cooperative mode or an uncooperative mode. The flight tests themselves and the parameters extracted serve as additional means of validating the DMS for this particular airplane.

The flight test runs utilized in this study are longitudinal responses generated by stabilator deflections in the neighborhood of $\pm 5^O$. The changes in angle of attack and pitching velocity are typically $\pm 10^O$ and $\pm 20^O$ per second, respectively. Normal acceleration responses are between +4g and -1g. The parameters extracted were the standard body-axis longitudinal stability and control derivatives.

SYMBOLS

Measurements and calculations were made in the U.S. Customary Units. They are presented herein in the International System of Units (SI) with the equivalent values in the U.S. Customary Units given parenthetically.

a_z normal acceleration (positive down), g units

C_m pitching-moment coefficient

$C_{m,o}$ pitching-moment coefficient at $\alpha = \delta = 0$

$$C_{m_q} = \frac{\partial C_m}{\partial \left(\frac{q\bar{c}}{2V}\right)} \text{ per radian}$$

$C_{m_q} + C_{m_{\dot{\alpha}}}$ damping-in-pitch derivative, $\dfrac{\partial C_m}{\partial \left(\frac{q\bar{c}}{2V}\right)} + \dfrac{\partial C_m}{\partial \left(\frac{\dot{\alpha}\bar{c}}{2V}\right)}$, per radian

C_{m_α} static longitudinal stability derivative, $\dfrac{\partial C_m}{\partial \alpha}$, per radian

$$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial \left(\frac{\dot{\alpha}\bar{c}}{2V}\right)} \text{ per radian}$$

$(C_m)_{\alpha_T,\delta_T}$ pitching-moment coefficient at $\alpha = \alpha_T$, $\delta = \delta_T$

C_{m_δ} pitch-control-effectiveness derivative, $\dfrac{\partial C_m}{\partial \delta}$, per radian

C_X longitudinal-force coefficient

$C_{X_q} = \dfrac{\partial C_X}{\partial\left(\dfrac{q\bar{c}}{2V}\right)}$ per radian

$C_{X_\alpha} = \dfrac{\partial C_X}{\partial \alpha}$ per radian

$(C_X)_{\alpha_T,\delta_T}$ longitudinal-force coefficient at $\alpha = \alpha_T$, $\delta = \delta_T$

C_Z normal-force coefficient

$C_{Z,o}$ normal-force coefficient at $\alpha = \delta = 0$

$C_{Z_q} = \dfrac{\partial C_Z}{\partial\left(\dfrac{q\bar{c}}{2V}\right)}$ per radian

C_{Z_α} slope of normal-force curve, $\dfrac{\partial C_Z}{\partial \alpha}$, per radian

$(C_Z)_{\alpha_T,\delta_T}$ normal-force coefficient at $\alpha = \alpha_T$, $\delta = \delta_T$

$C_{Z_\delta} = \dfrac{\partial C_Z}{\partial \delta}$ per radian

$\bar{c}$ mean aerodynamic chord, meters (ft)

g acceleration due to gravity, meters/second^2 (ft/sec^2)

I_Y aircraft moment of inertia about the Y-axis, kilogram-meters^2 (slug-ft^2)

M Mach number

m   mass of fueled airplane, kilograms   (slugs)

q   pitching angular velocity, radians/second

$\dot{q}$ pitching acceleration, radians/second^2

$\bar{q}$ dynamic pressure, $\frac{1}{2}\rho V^2$, newtons/meter^2 (lb/ft^2)

S   wing area, meters^2 (ft^2)

u   velocity along horizontal body axis, meters/second   (ft/sec)

$\dot{u}$ acceleration along horizontal body axis, meters/second^2 (ft/sec^2)

V   true airspeed, meters/second   (ft/sec)

w   velocity along vertical body axis, meters/second   (ft/sec)

$\dot{w}$ acceleration along vertical body axis, meters/second^2 (ft/sec^2)

α angle of attack, radians

$\dot{\alpha}$ rate of change of angle of attack, radians/second

α_T trim angle of attack, radians

δ stabilator deflection angle, radians

δ_T stabilator deflection angle at trim, radians

θ pitch angle, radians

$\dot{\theta}$ rate of change of pitch angle, radians/second

ρ mass density of air, kilograms/meter^3 (slugs/ft^3)

ω_n natural frequency of the pitching-moment oscillation for controls locked,
                radians/second

FLIGHT TESTS

The flight test data were provided by the U.S. Naval Air Test Center at Patuxent River, Maryland. The flight tests were conducted by Navy test pilots as part of an investigation with a McDonnell Douglas F-4 airplane. Five different longitudinal response runs were made: three during one flight test of the airplane and two during a second flight test. The first three runs were made at an altitude of approximately 1524 m (5000 ft) and at Mach numbers of about 0.6, 0.7, and 0.8, respectively. The other two runs were made at an altitude of approximately 6096 m (20 000 ft) and at Mach numbers of about 0.6 and 0.8, respectively. The stability augmentation system (SAS) was deactivated in order to provide full response for all the test runs.

For each of the test runs the procedure was identical. The airplane was trimmed by the pilot at the desired altitude and Mach number and held for a short period, and then a disturbing input was placed on the stabilators. The pilot task during the maneuver was to null any lateral motions. Since thrust was held constant during the maneuver and since altitude and Mach number were approximately constant throughout the maneuver, the translational modes of the airframe were not sufficiently excited to allow extraction of the longitudinal-force coefficient. A time history of the stabilator position for a typical test run is shown in figure 2(a). Shown in figure 2(b) are typical time histories of horizontal velocity u, vertical velocity w, pitching angular velocity q, and normal acceleration a_z. True airspeed was first determined from figure 1 of reference 5 using Mach number, pressure altitude, and temperature from flight tests and then resolved through angle-of-attack measurements to yield horizontal and vertical velocities.

Angle of attack was measured by means of a vane on a nose boom. The boom was assumed to be rigid. The readings were corrected for pitch by the Navy. Pitching velocity was measured by rate gyros located slightly forward and at the foot level of the pilot. Normal acceleration was measured by an accelerometer located in the left wheel well. The location of the instrumentation is shown in figure 1. However, the center-of-gravity offset of the accelerometer was negligible for longitudinal responses. (No documentation was available from the Navy as to the accuracy of the instrumentation.)

The data for each run were sampled at 0.1-sec intervals. Each of these points was used by the computer program but every other point is plotted in all time history figures to avoid crowding. No smoothing techniques were applied to the data provided. The data were supplied to Langley Research Center in tabular form but were transferred to magnetic tape for use with the computer program.

COMPUTATIONAL METHOD

The equations of motion used by the computer program for longitudinal motion are as follows:

$$\dot{u} = -g \sin \theta - wq + \frac{1}{2} \frac{\rho V^2 S}{m} \left[(C_X)_{\alpha_T, \delta_T} + C_{X_\alpha}(\alpha - \alpha_T) + C_{X_q} \frac{q\bar{c}}{2V} \right]$$

$$\dot{w} = g \cos \theta + uq + \frac{1}{2} \frac{\rho V^2 S}{m} \left[(C_Z)_{\alpha_T, \delta_T} + C_{Z_\alpha}(\alpha - \alpha_T) + C_{Z_q} \frac{q\bar{c}}{2V} + C_{Z_\delta}(\delta - \delta_T) \right]$$

$$\dot{q} = \frac{1}{2} \frac{\rho V^2 S \bar{c}}{I_Y} \left[(C_m)_{\alpha_T, \delta_T} + C_{m_\alpha}(\alpha - \alpha_T) + C_{m_{\dot{\alpha}}} \frac{\dot{\alpha}\bar{c}}{2V} + C_{m_q} \frac{q\bar{c}}{2V} + C_{m_\alpha}(\delta - \delta_T) \right]$$

$$\dot{\theta} = q$$

$$a_z = \dot{w} - g \cos \theta - qu$$

$$\dot{\alpha} \approx \frac{\dot{w}}{u}$$

$$\alpha = \tan^{-1} \frac{w}{u}$$

$$V = \sqrt{u^2 + w^2}$$

Again, it should be noted that the form of input excitation (pitch doublet yielding the short-period motion) makes the extraction of longitudinal-force coefficients $(C_X$ derivatives$)$ infeasible, since $\dot{u}$ is negligible. However, the program extracts a set of C_X derivatives that provide a longitudinal response to match the flight data; thus, a proper representation of true airspeed is ensured.

The method of parameter estimation incorporated into the computer program is based on maximum likelihood estimation. This method is inherently iterative and requires an initial estimate for each derivative in order to begin the extraction process. Reference 1 describes in detail both the method of extraction and the computer program. It should be emphasized, however, that the procedure for extracting the derivatives is not straightforward. Engineering judgment tempered with estimator statistics, such as the variance of individual derivatives and intercorrelation coefficients, plays a significant role in the extraction procedure; thus, the capability of analyst program interaction is highly desirable.

RESULTS

Figure 3 illustrates the response of the mathematical model to a typical set of starting values; the flight data are included for comparison. Usually 8 to 10 iterations are required before initial convergence is obtained. From this base, engineering judgment and statistical information are used to eliminate all possible inconsistencies between aerodynamic principles and statistical results.

The conditions for the five flight tests are listed in table I. In figure 4 are presented the model responses generated by the final estimates of the stability derivatives for the five flight test runs and the respective flight test data. Again, it should be noted that the flight data displayed have not been filtered.

The total set of extracted stability and control derivatives for each flight test run and the standard deviation of each derivative are listed in table II. The intercept derivatives $C_{Z,o}$ and $C_{m,o}$ are defined at zero angle of attack and zero stabilator deflection.

From the set of extracted derivatives for the test airplane, the five principal derivatives C_{Z_α}, C_{Z_δ}, C_{m_α}, $C_{m_q} + C_{m_{\dot\alpha}}$, and C_{m_δ} are plotted as a function of Mach number and compared with the manufacturer's data for an earlier version in figures 5 to 9. (It should be noted that the center-of-gravity variation between the flight test runs is less than 0.55% about 31.80% $\bar{c}$.) Aerodynamic differences between the two airplanes are believed to be small and, hence, two different sets of estimates of the principal derivatives exist to predict airplane response.

The five principal derivatives taken from the manufacturer's data were fixed as constants in the program and the minor derivatives $\left((C_X)_{\alpha_T,\delta_T}, \ C_{X_\alpha}, \ C_{X_q}, \ (C_Z)_{\alpha_T,\delta_T}, \ C_{Z_q}, \ (C_m)_{\alpha_T,\delta_T}\right)$ were extracted from the flight data by the maximum likelihood algorithm. This procedure yielded the model responses presented in figure 10 for the five flight test runs. These results clearly indicate an error in both frequency and amplitude for normal acceleration a_Z and an error in amplitude for vertical velocity w. The issue now is to uncover the manufacturer's estimates that give rise to the errors. Examination of figures 5 to 9 reveals that the largest discrepancy occurs in the estimates of the static longitudinal stability derivative C_{m_α} and, therefore, the error analysis was begun with this derivative.

The principal derivatives taken from the extracted set were used in conjunction with the manufacturer's values of C_{m_α} to generate the responses shown in figure 11; the minor derivatives were extracted in the usual manner. These results clearly indicate an error in frequency for all the variables.

In a final attempt to use the manufacturer's value of C_{m_α}, this derivative was fixed at the manufacturer's value and the algorithm was allowed to select the values of

all other derivatives. This procedure converged for all flight test runs with the exception of test run 4, which diverged. The resulting model responses with the respective flight test data are presented in figure 12 for test runs 1, 2, 3, and 5. Again, an error exists in both frequency and amplitude for normal acceleration a_z and an error exists in amplitude for vertical velocity w.

On the basis of these results, it is concluded that the flight test data require a much lower value for the static longitudinal stability derivative C_{m_α} than that presented by the manufacturer. As further verification of this conclusion, values of the static longitudinal stability derivative were calculated by using the following equation:

$$\left| C_{m_\alpha} \right| = \frac{\omega_n^2 I_Y}{\bar{q} S \bar{c}} \tag{1}$$

These calculations were made from the flight test data after input excitation had essentially ceased. The results of these calculations are presented in figure 7. The calculations yielded values of C_{m_α} which agreed more closely with the extracted values than with the manufacturer's data.

At this point in the error analysis, at least one discrepancy has been shown to be significant. To determine discrepancies among the remaining four principal derivatives, the following procedure was used. The four principal derivatives taken from the manufacturer's data were fixed as constants in the program, and the minor derivatives as well as C_{m_α} were extracted in the usual manner. This procedure yielded the model responses presented in figure 13 and the variation of C_{m_α} with Mach number presented in figure 14. Although the model responses for this procedure are quite good, the least-squares residual for fitting the flight data is inferior to that of the extracted set presented in table II. Therefore, it is believed that good agreement exists for all principal derivatives with the exception of the static longitudinal stability derivative C_{m_α}. Also, it should be noted that this procedure yielded values for C_{m_α} that agreed more closely with the extracted values than with the manufacturer's data.

CONCLUDING REMARKS

It is believed that the agreement between the extracted values and the manufacturer's data for four of the five principal derivatives $\left(C_{Z_\alpha}, \ C_{Z_\delta}, \ C_{m_q} + C_{m_{\dot{\alpha}}}, \ C_{m_\delta} \right)$, and the extensive investigation carried out on the fifth principal derivative C_{m_α} establish not only the merits of maximum likelihood estimation in a real-world environment but also the merits of the interactive capabilities of the computer implementation utilized to carry out the investigation. The investigation of C_{m_α} revealed that the flight test data require

a much lower value for the static longitudinal stability derivative than that presented by the manufacturer.

The present study also provided some of the data to validate the Langley differential maneuvering simulator (DMS) program.

Langley Research Center,
      National Aeronautics and Space Administration,
            Hampton, Va., January 19, 1972.

REFERENCES

1. Grove, Randall D.; Bowles, Roland L.; and Mayhew, Stanley C.: A Procedure for Estimating Stability and Control Parameters From Flight Test Data by Using Maximum Likelihood Methods Employing a Real-Time Digital System. NASA TN D-6735, 1972.

2. White, Ellis: Eastern Simulation Council Meeting. Simulation, vol. 12, no. 2, Feb. 1969, pp. 53-56.

3. Copeland, J. L.; Kahlbaum, W. M., Jr.; Barker, L. E., Jr.; Steinmetz, G. G.; and Grove, R. D.: The Design of a Dual Wide Angle Visual Cue Simulator and the Analysis of Multiaxis Projection Equipment. AIAA Paper No. 70-360, Mar. 1970.

4. Bonine, W. J.; Niemann, C. R.; Sonntag, A. H.; and Weber, W. B.: Model F/RF-4B-C Aerodynamic Derivatives. Rep. 9842, McDonnell Aircraft Corp., Feb. 10, 1964. (Rev. Aug. 1, 1968.)

5. Aiken, William S., Jr.: Standard Nomenclature for Airspeeds With Tables and Charts for Use in Calculation of Airspeed. NACA Rep. 837, 1946. (Supersedes NACA TN 1120.)

TABLE I.- FLIGHT TEST CONDITIONS

Test run	Altitude		Mach number	Input	Excitation	Center of gravity
	m	ft				
1	1524	5 000	0.6	Pitch doublet	Short-period motion	31.80% $\bar{c}$
2	1524	5 000	.7	Pitch doublet	Short-period motion	31.47% $\bar{c}$
3	1524	5 000	.8	Pitch doublet	Short-period motion	31.27% $\bar{c}$
4	6096	20 000	.6	Pitch doublet	Short-period motion	32.22% $\bar{c}$
5	6096	20 000	.8	Pitch doublet	Short-period motion	31.52% $\bar{c}$

TABLE II.- EXTRACTED STABILITY AND CONTROL DERIVATIVES

Derivative	Test run 1 (c.g. = 31.80% $\bar{c}$)		Test run 2 (c.g. = 31.47% $\bar{c}$)		Test run 3 (c.g. = 31.27% $\bar{c}$)		Test run 4 (c.g. = 32.22% $\bar{c}$)		Test run 5 (c.g. = 31.52% $\bar{c}$)	
	Extracted value	Standard deviation	Extracted value	Standard deviation	Extracted value	Standard deviation	Extracted value	Standard deviation	Extracted value	Standard deviation
$C_{m,o}$	0.0193	0.00008	0.0156	0.00008	0.0148	0.0002	0.0217	0.0001	0.0177	0.0001
C_{m_α}	-.106	.0017	-.126	.0026	-.167	.0037	-.109	.0009	-.163	.0013
$C_{m_q} + C_{m_{\dot\alpha}}$	-3.32	.06	-3.11	.08	-3.30	.11	-4.09	.04	-3.93	.05
C_{m_δ}	.576	.009	.555	.015	.540	.020	.618	.010	.600	.010
$C_{Z,o}$	-.080	.004	-.086	.004	-.106	.005	-.025	.004	-.049	.004
C_{Z_α}	-3.36	.07	-3.33	.10	-3.64	.10	-3.50	.04	-3.78	.06
C_{Z_δ}	.346	.018	.334	.019	.325	.022	.372	.018	.361	.017
C_{Z_q}	Unidentifiable due to insensitivity									
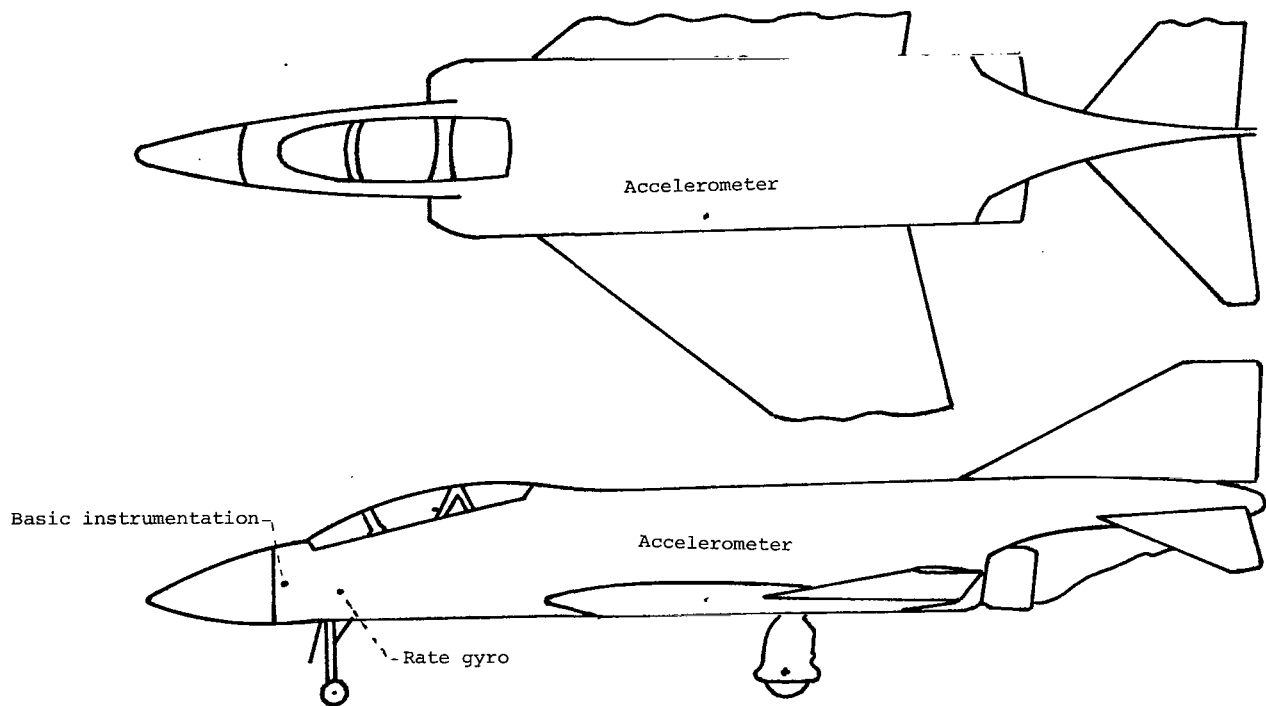
Figure 1.- Diagram of test airplane.

Time, sec
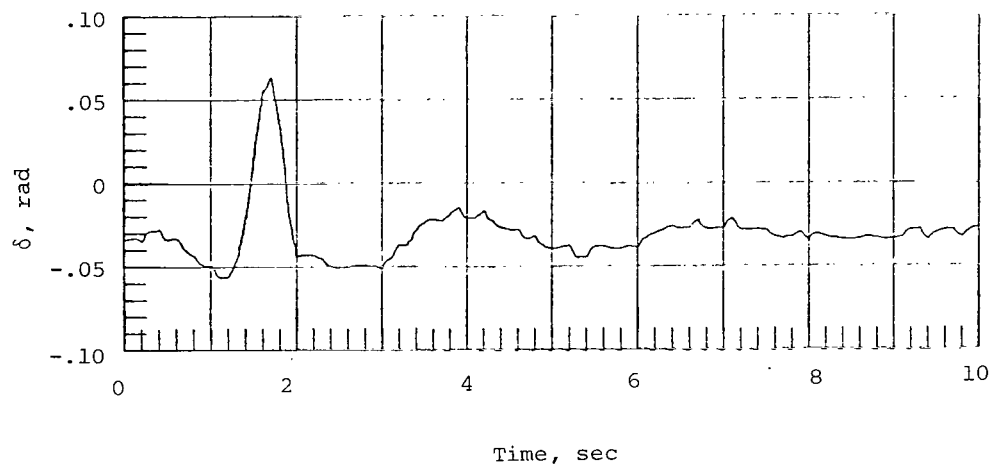
(a) Time history of stabilator deflection angle.

Figure 2.- Typical flight data.

12
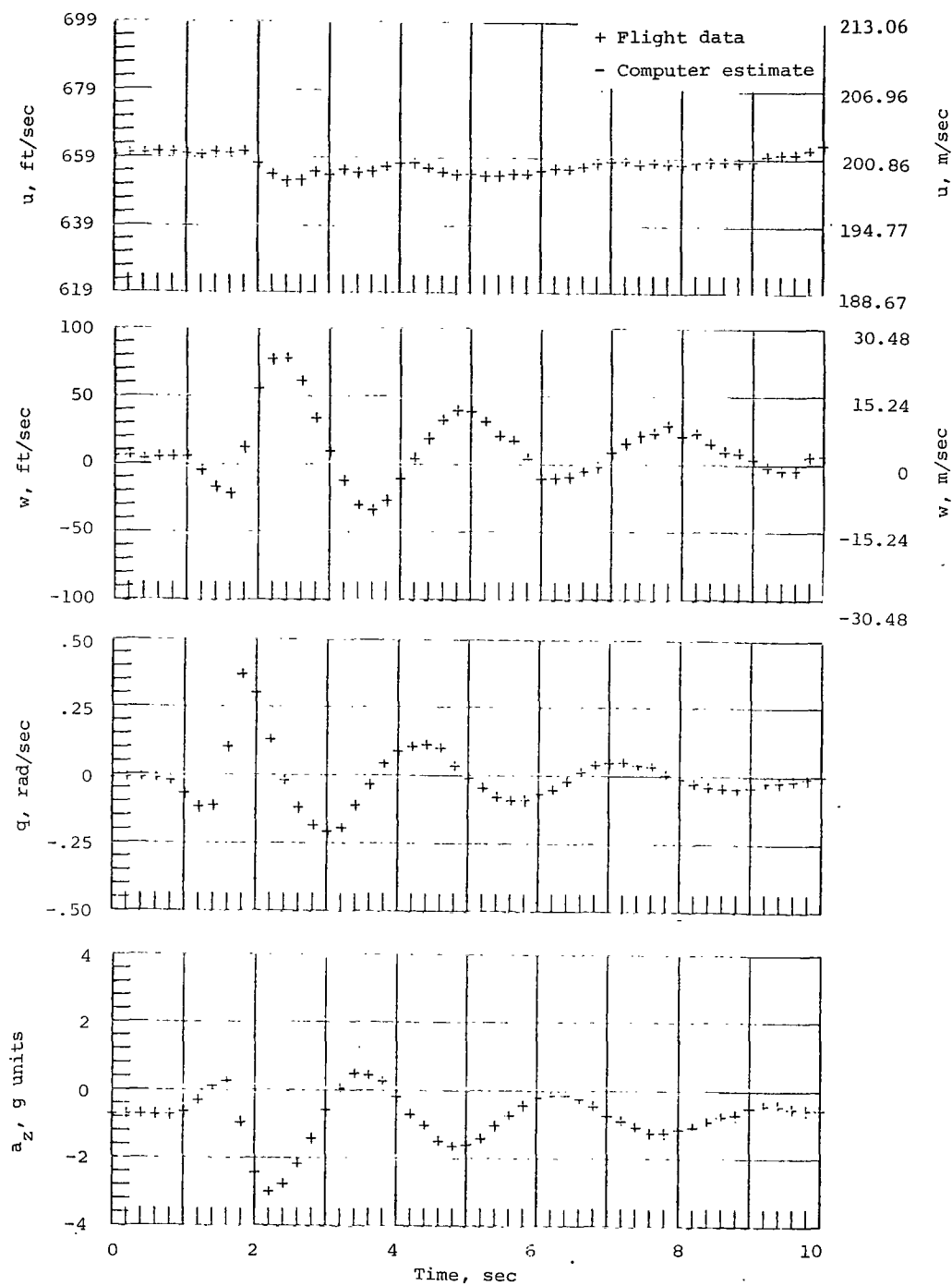
(b) Time histories of horizontal velocity, vertical velocity,
pitching velocity, and normal acceleration.

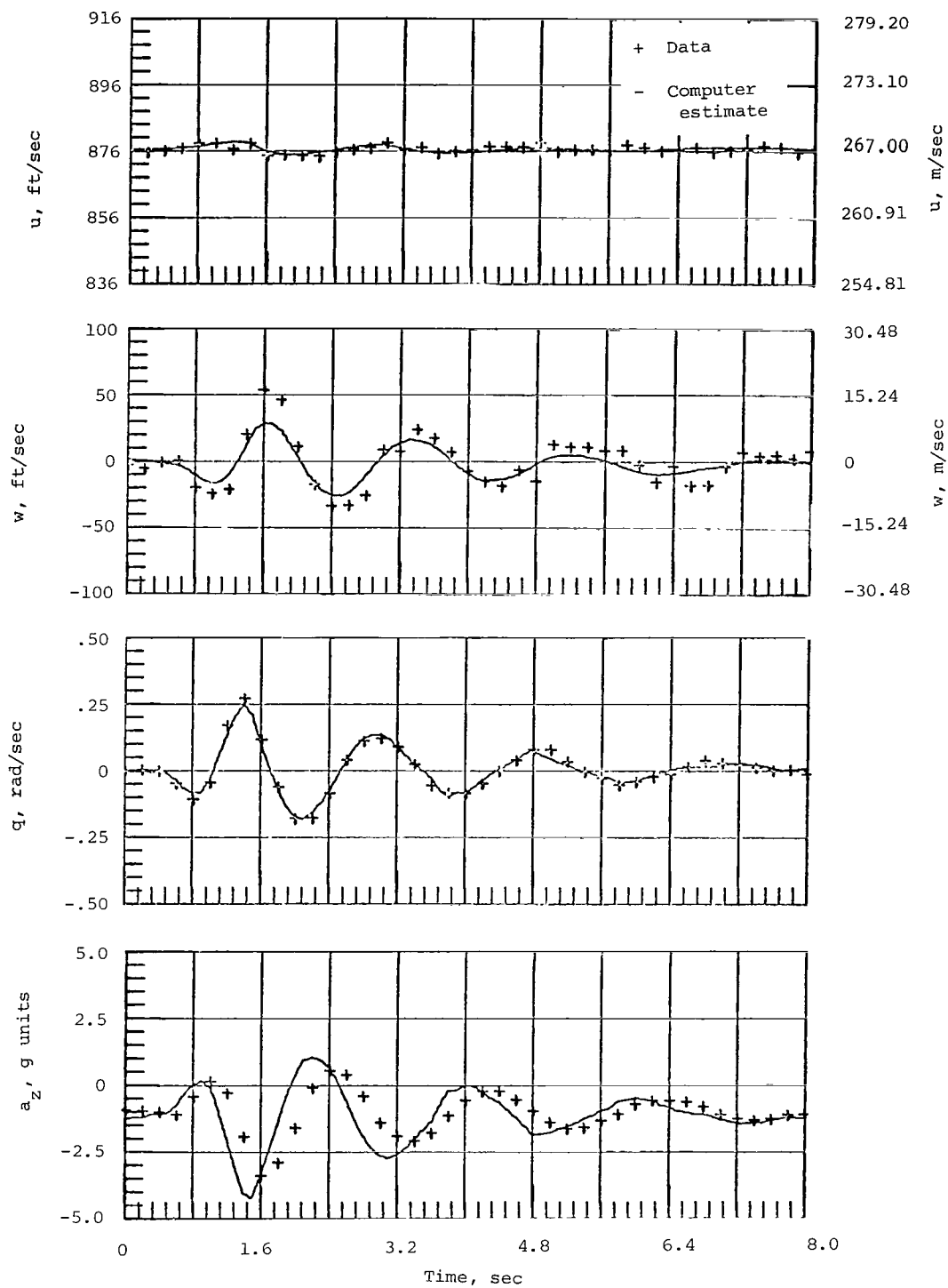Figure 2.- Concluded.
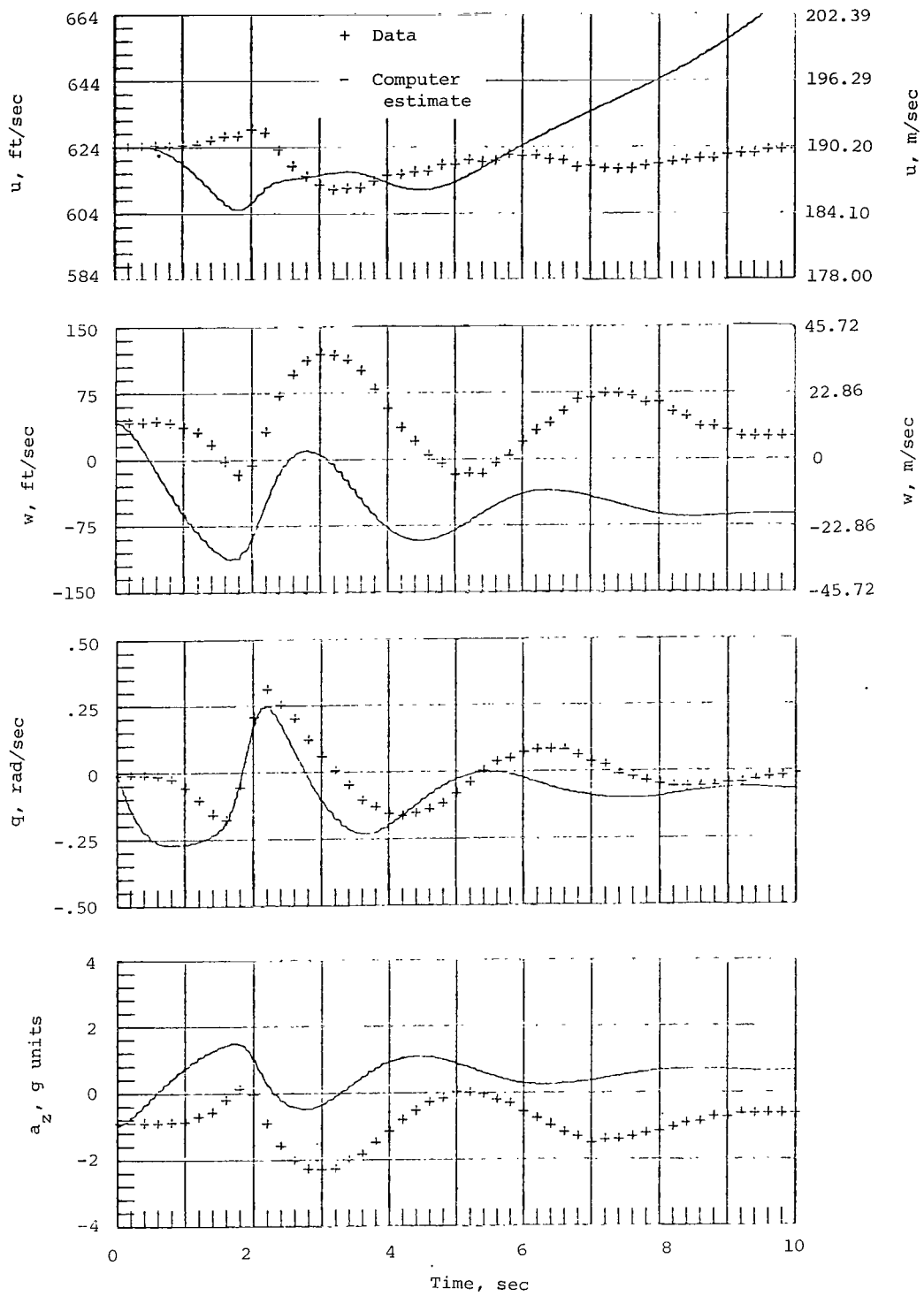
Figure 3.- Responses to typical starting values.
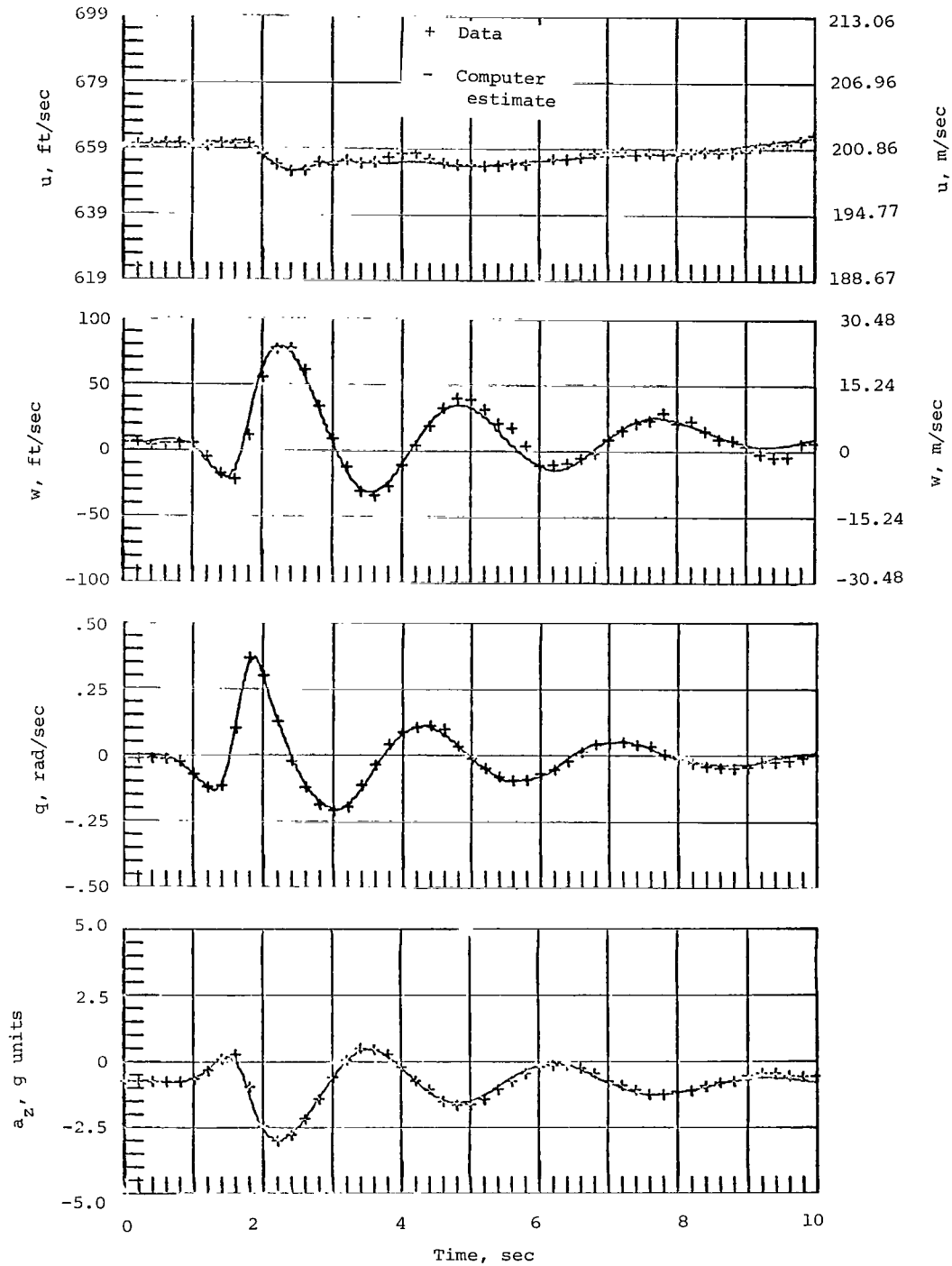
(a) Test run 1.

Figure 4.- Final model responses generated by extracted derivative estimates.
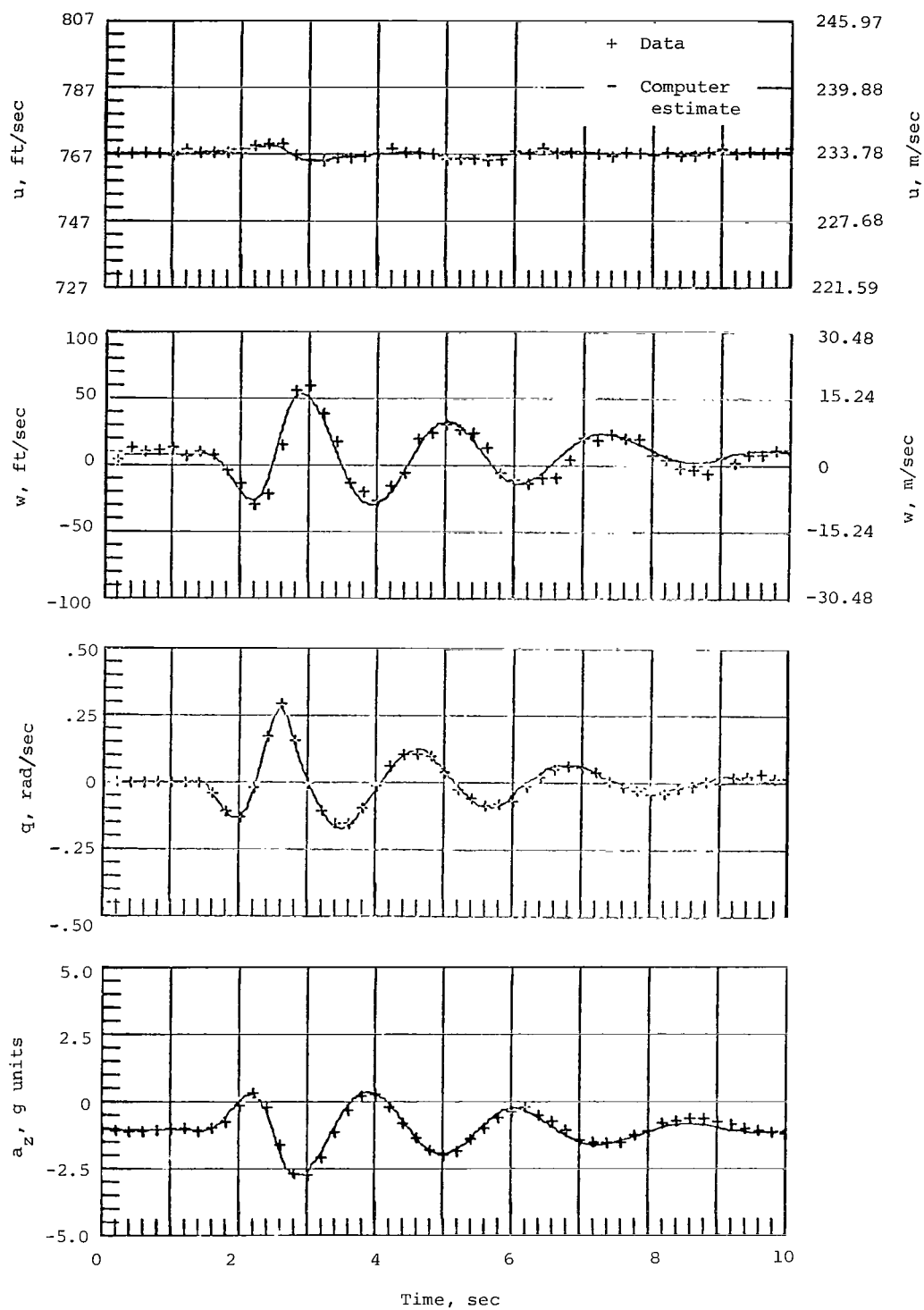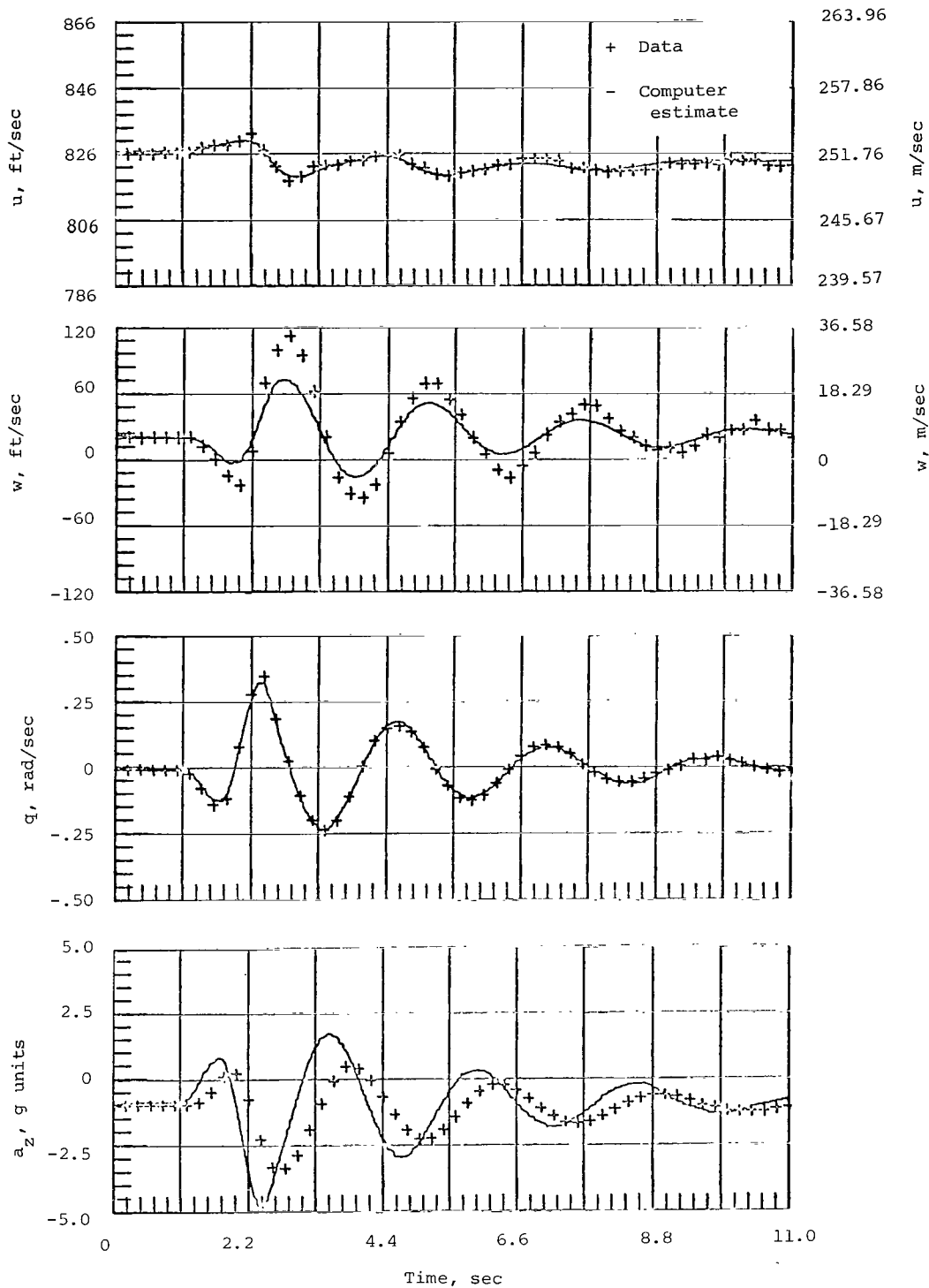
(b) Test run 2.

Figure 4.- Continued.
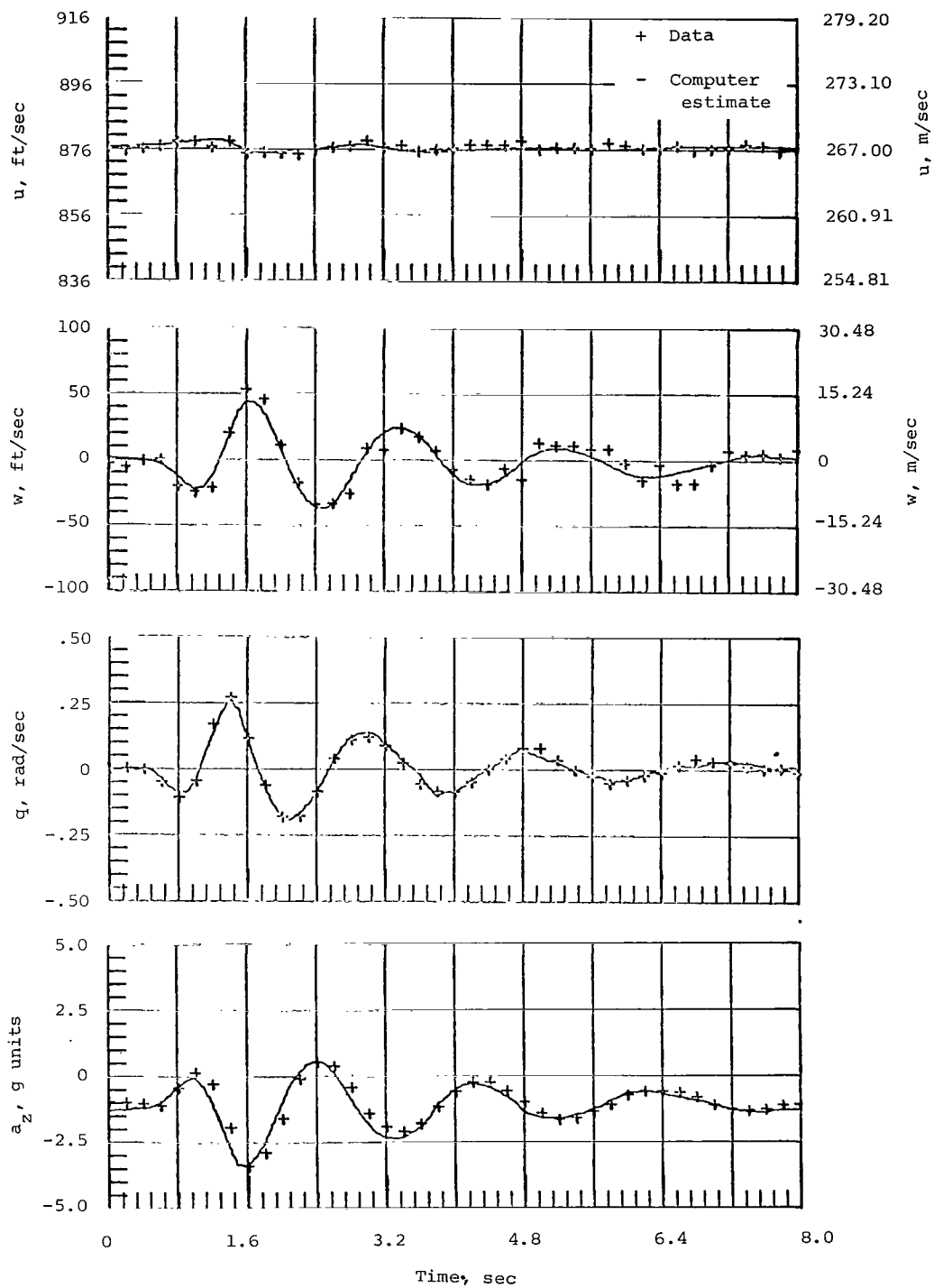
(c) Test run 3.

Figure 4.- Continued.
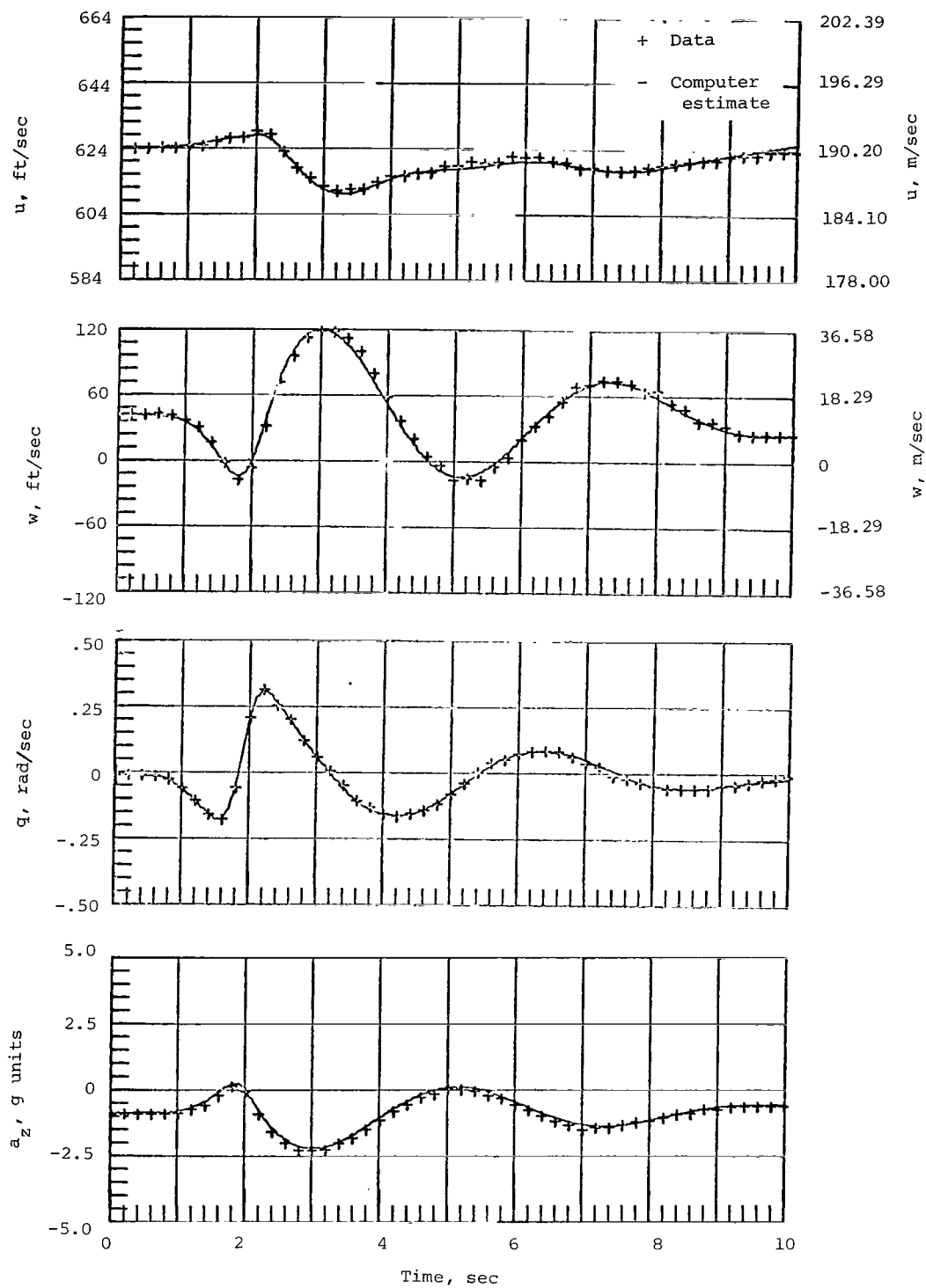
(d) Test run 4.

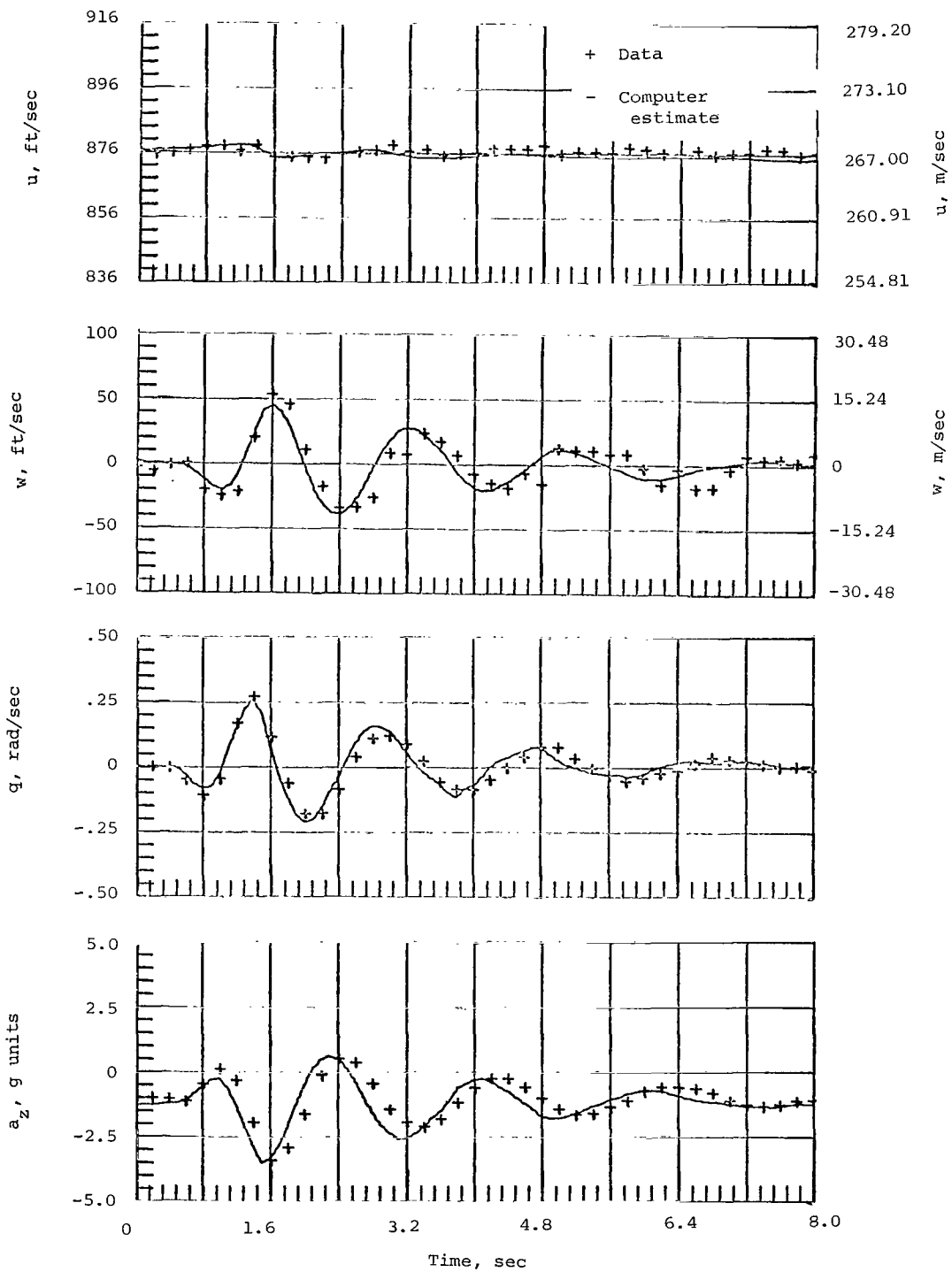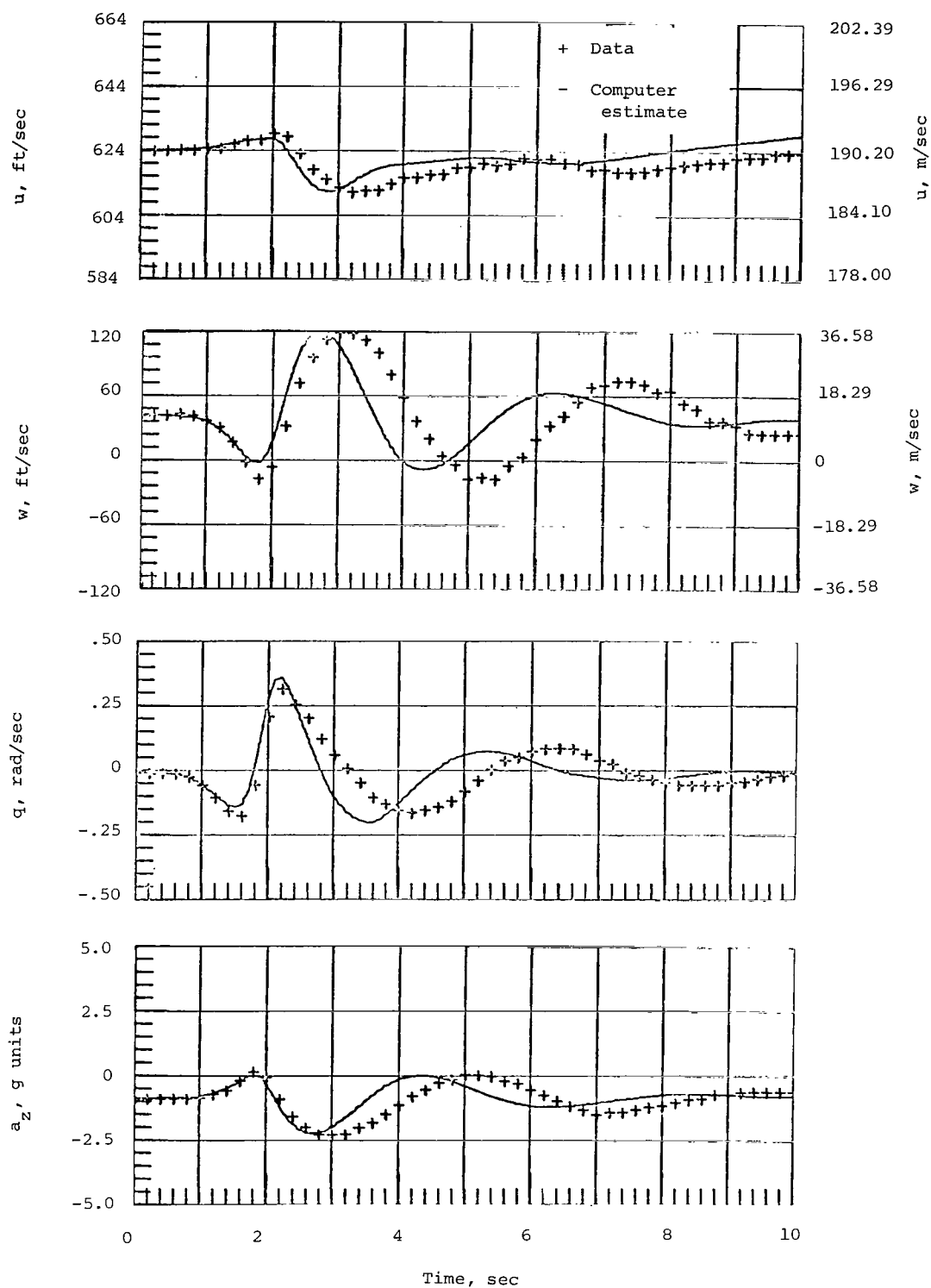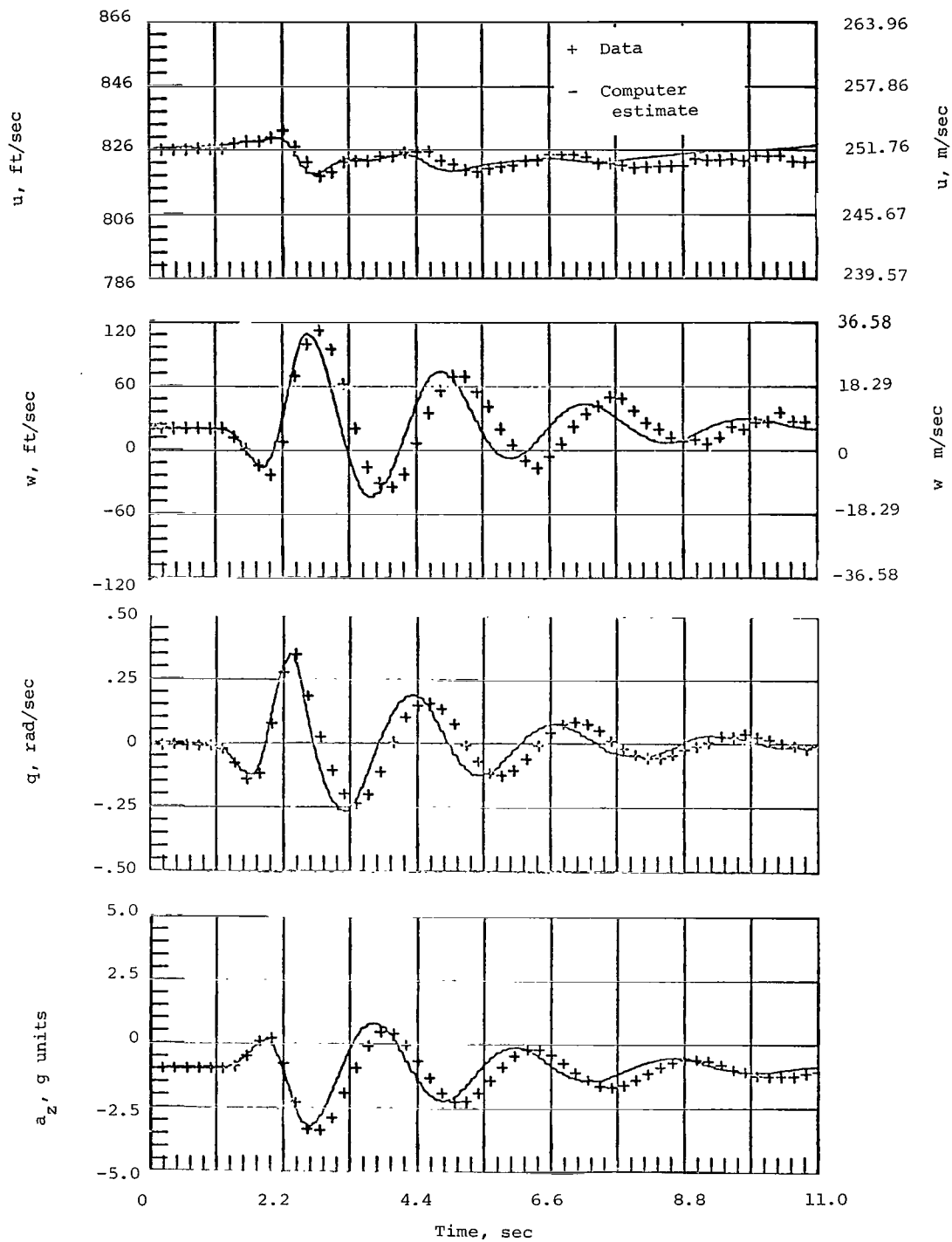Figure 4.- Continued.
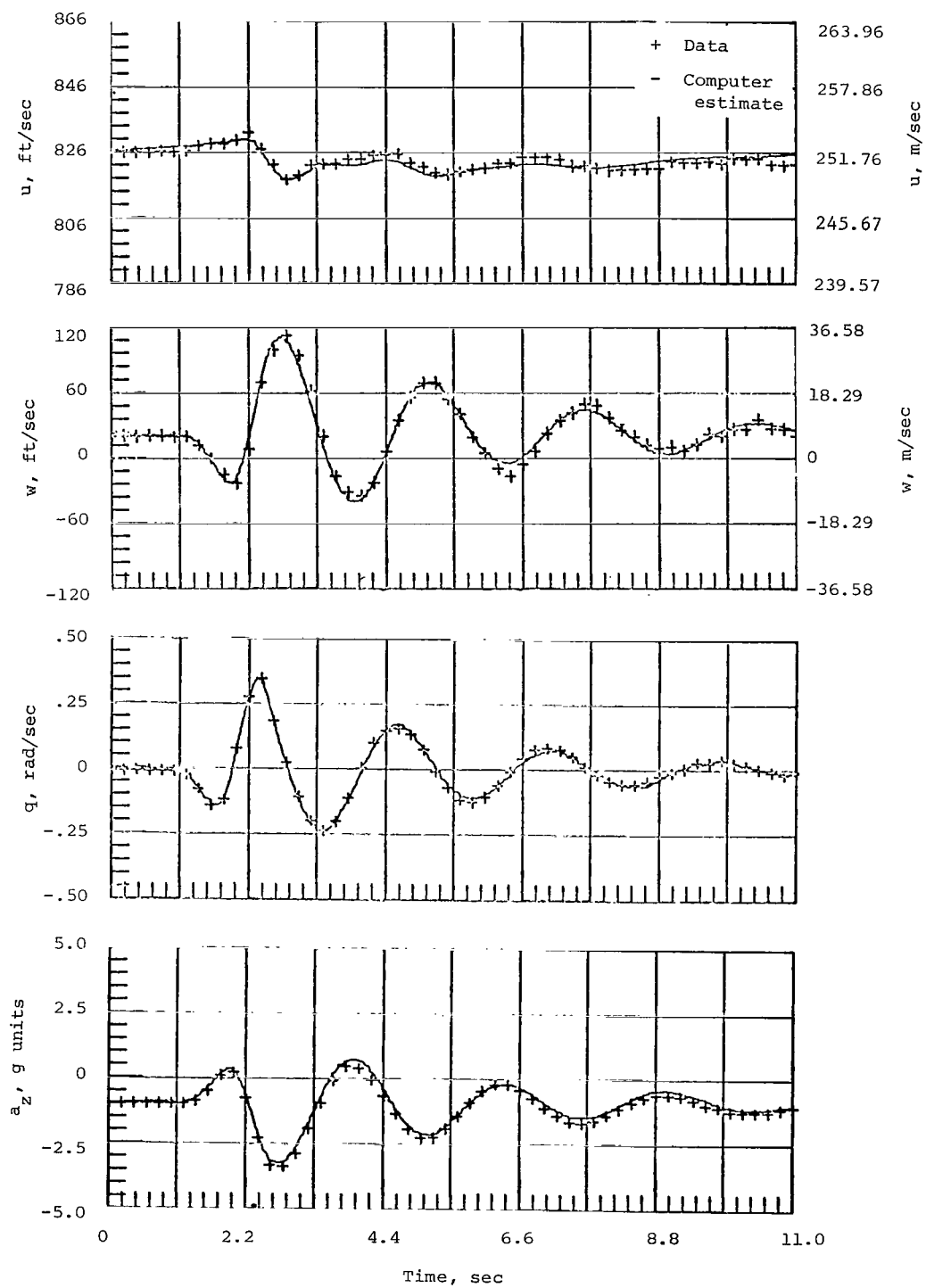
(e) Test run 5.

Figure 4.- Concluded.

Figure 5.- Variation of C_{Z_α} with Mach number.

△   Extracted from flight; 1524 m (5000 ft)

O   Extracted from flight; 6096 m (20000 ft)

——— Manufacturer's data, c.g.=31%c̄; 1524 m (5000 ft)

- - - - Manufacturer's data, c.g.=31%c̄; 6096 m (20000 ft)
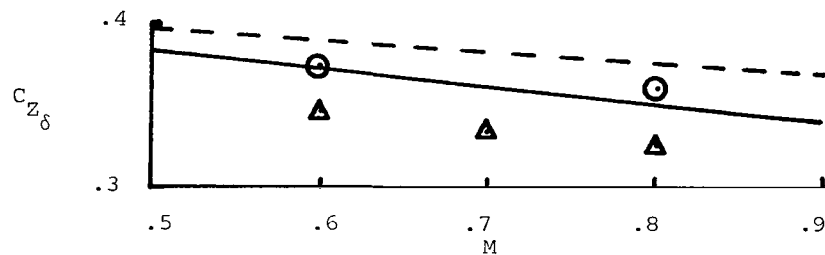
Figure 6.- Variation of C_{Z_δ} with Mach number.

20
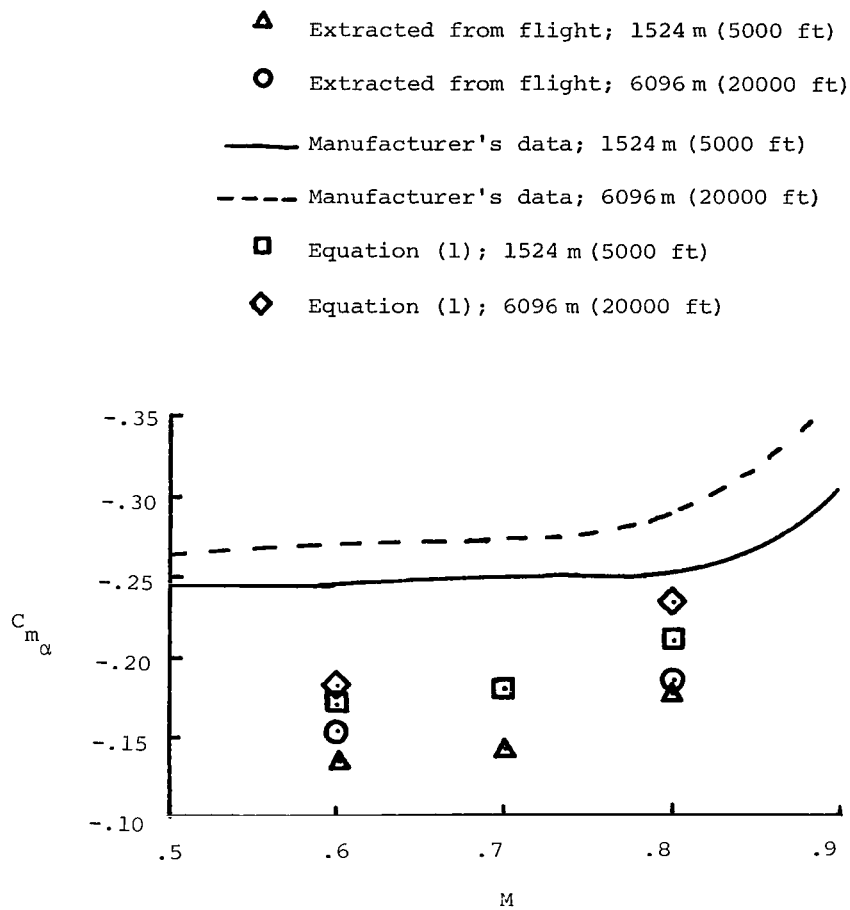
Figure 7.- Variation of C_{m_α} with Mach number. All data corrected to c.g. = 31% $\bar{c}$.

Figure 8.- Variation of $C_{m_q} + C_{m_{\dot{\alpha}}}$ with Mach number.

△   Extracted from flight; 1524 m (5000 ft)

○   Extracted from flight; 6096 m (20000 ft)

────── Manufacturer's data (extrapolated), c.g.=31%$\bar{c}$; 1524 m (5000 ft)

── ── ── Manufacturer's data (extrapolated), c.g.=31%$\bar{c}$; 6096 m (20000 ft)
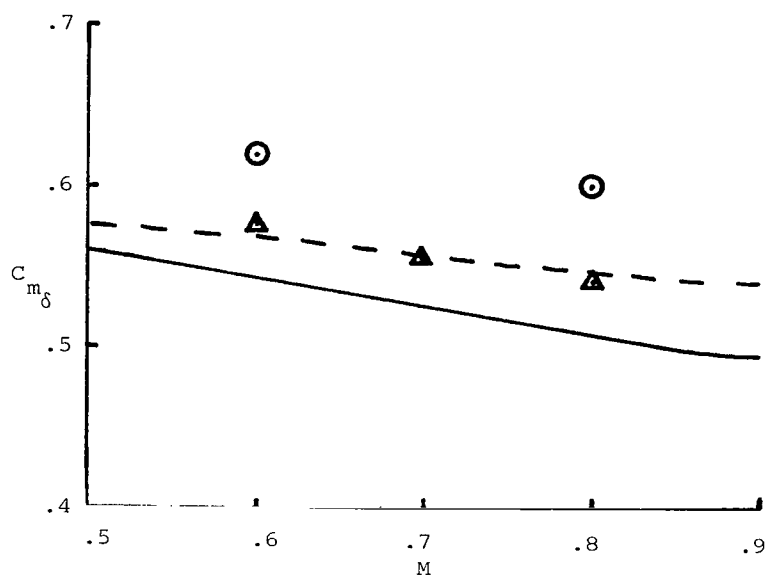
Figure 9.- Variation of C_{m_δ} with Mach number.
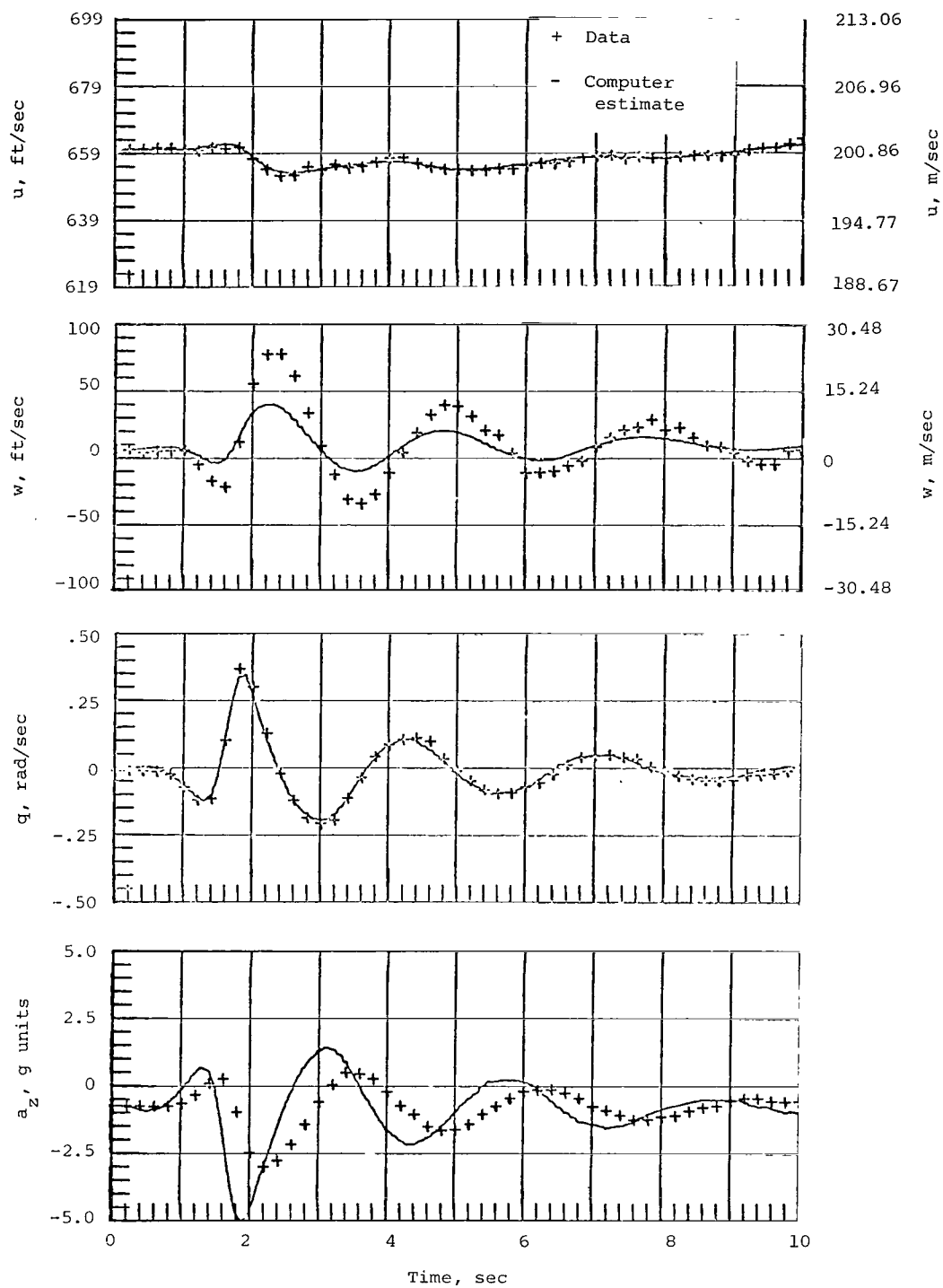
(a) Test run 1.

Figure 10.- Final model responses generated by using
manufacturer's derivative estimates.
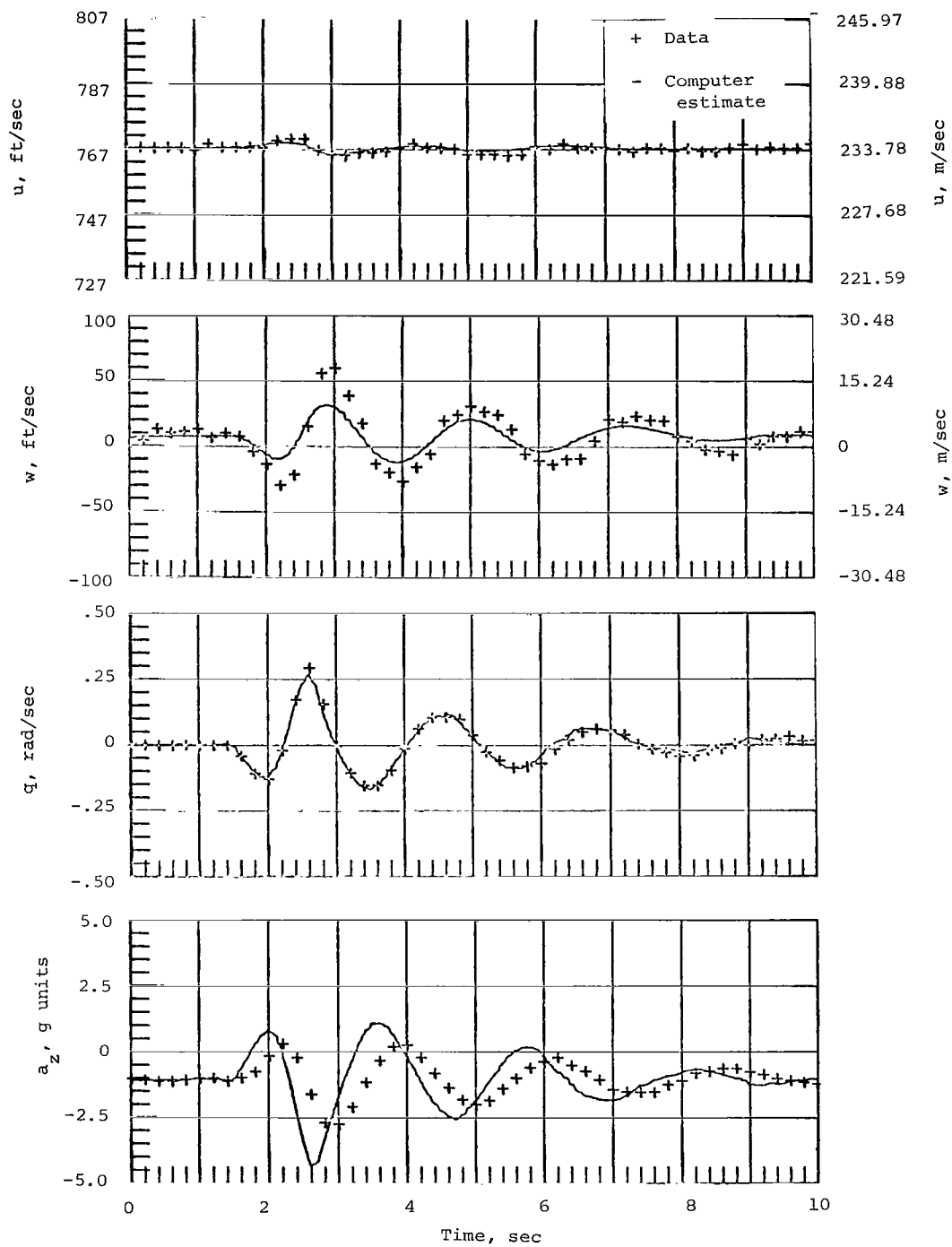
(b) Test run 2.

Figure 10.- Continued.

(c) Test run 3.

Figure 10.- Continued.
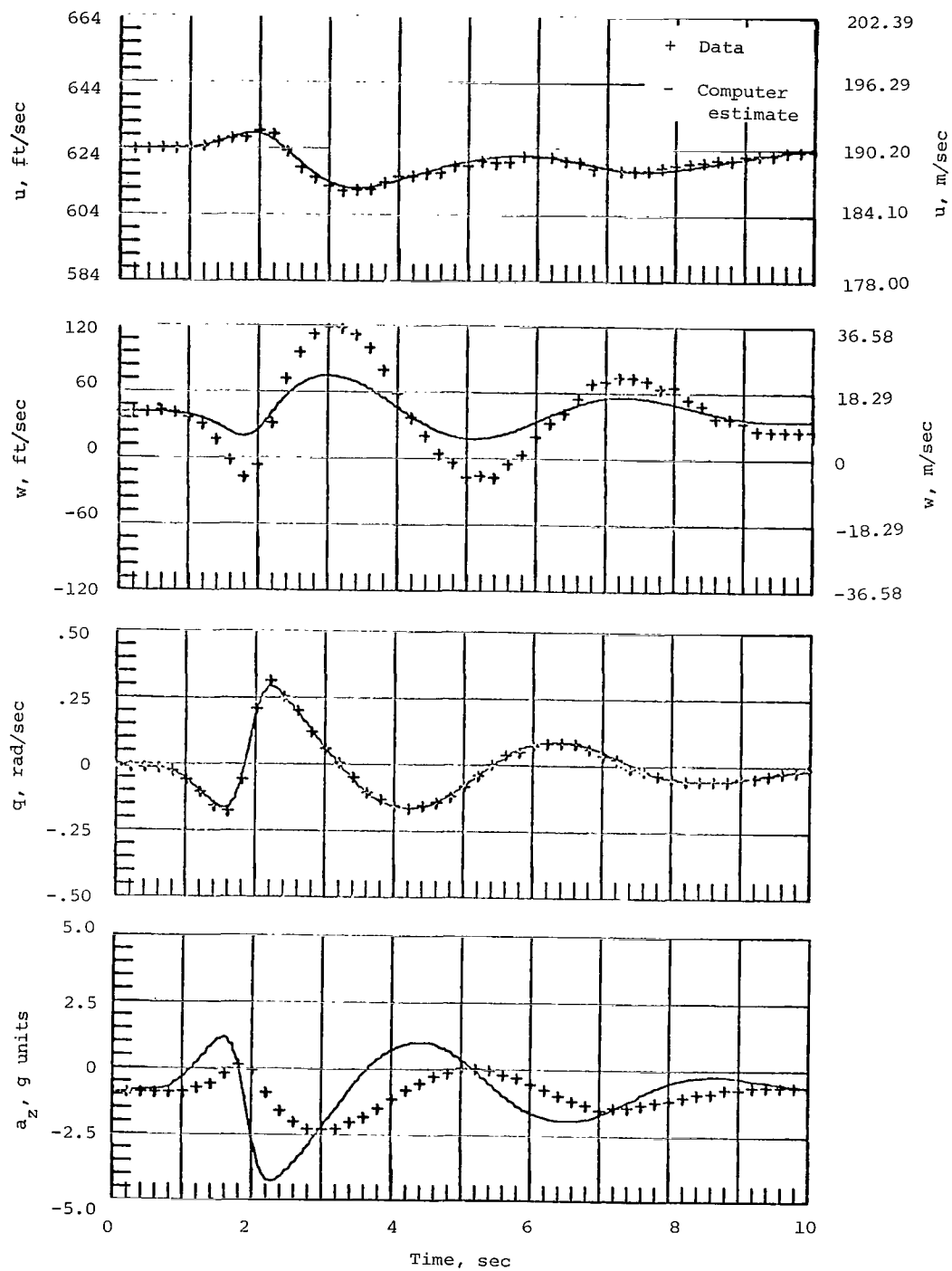
(d) Test run 4.

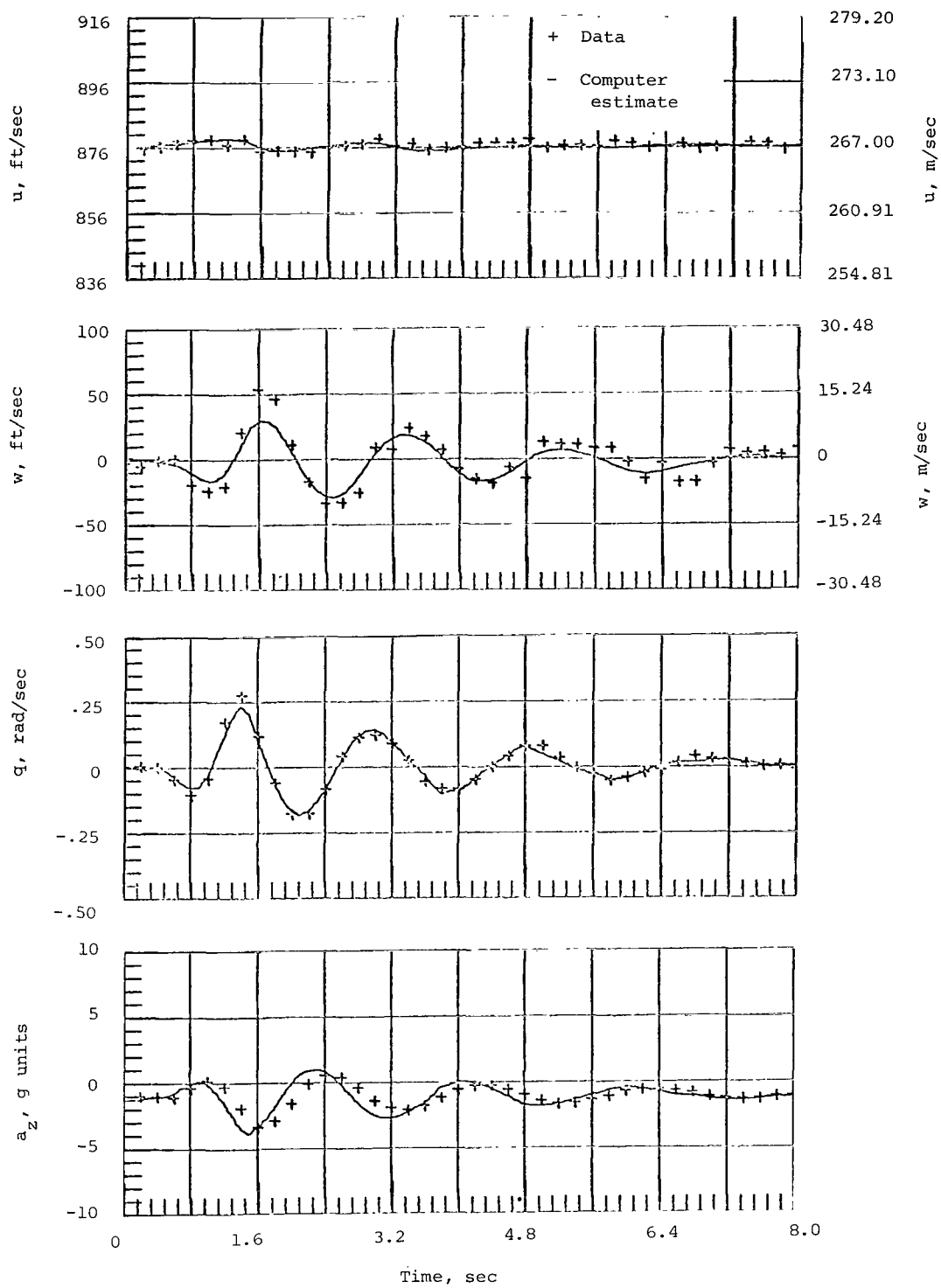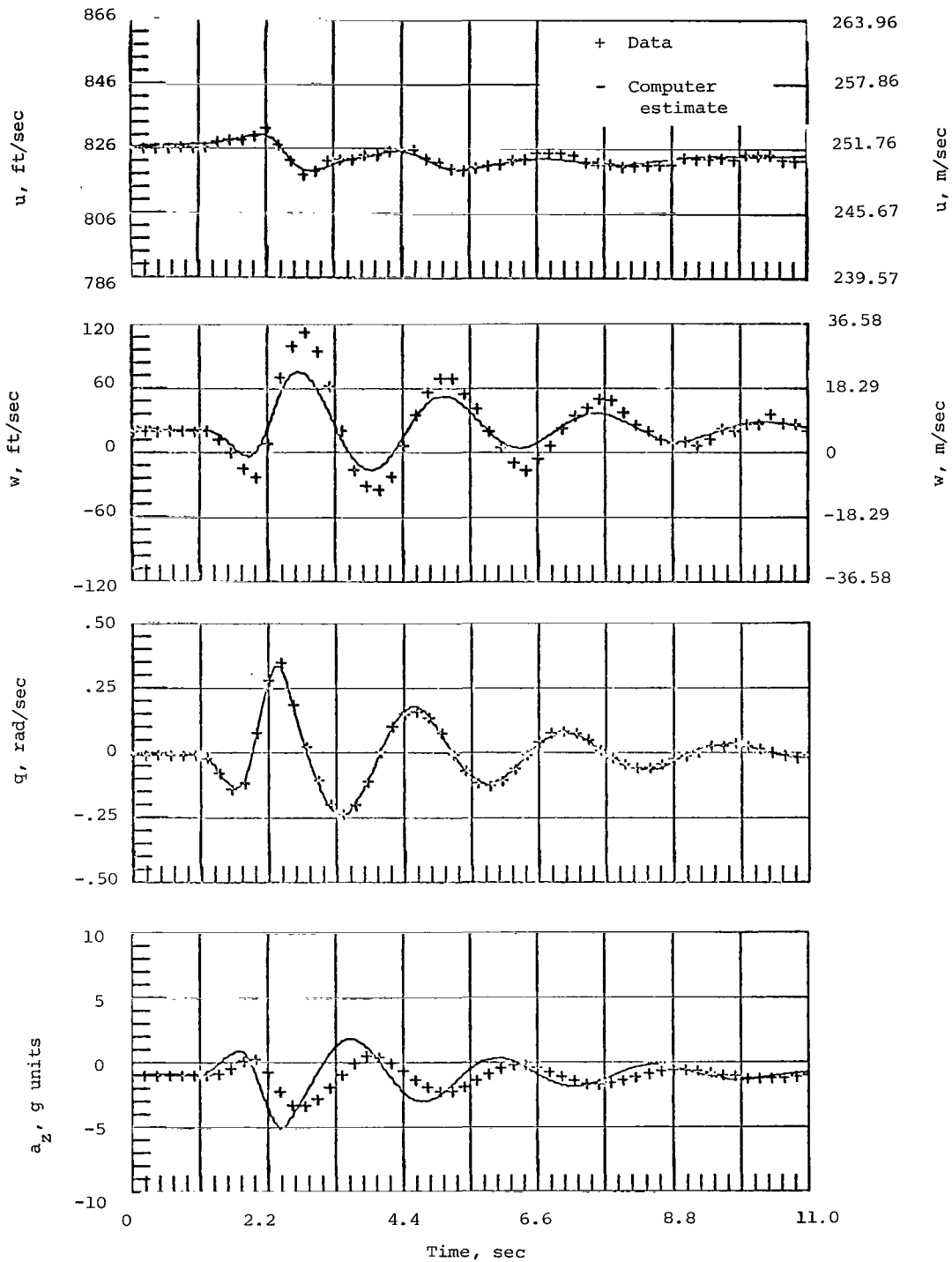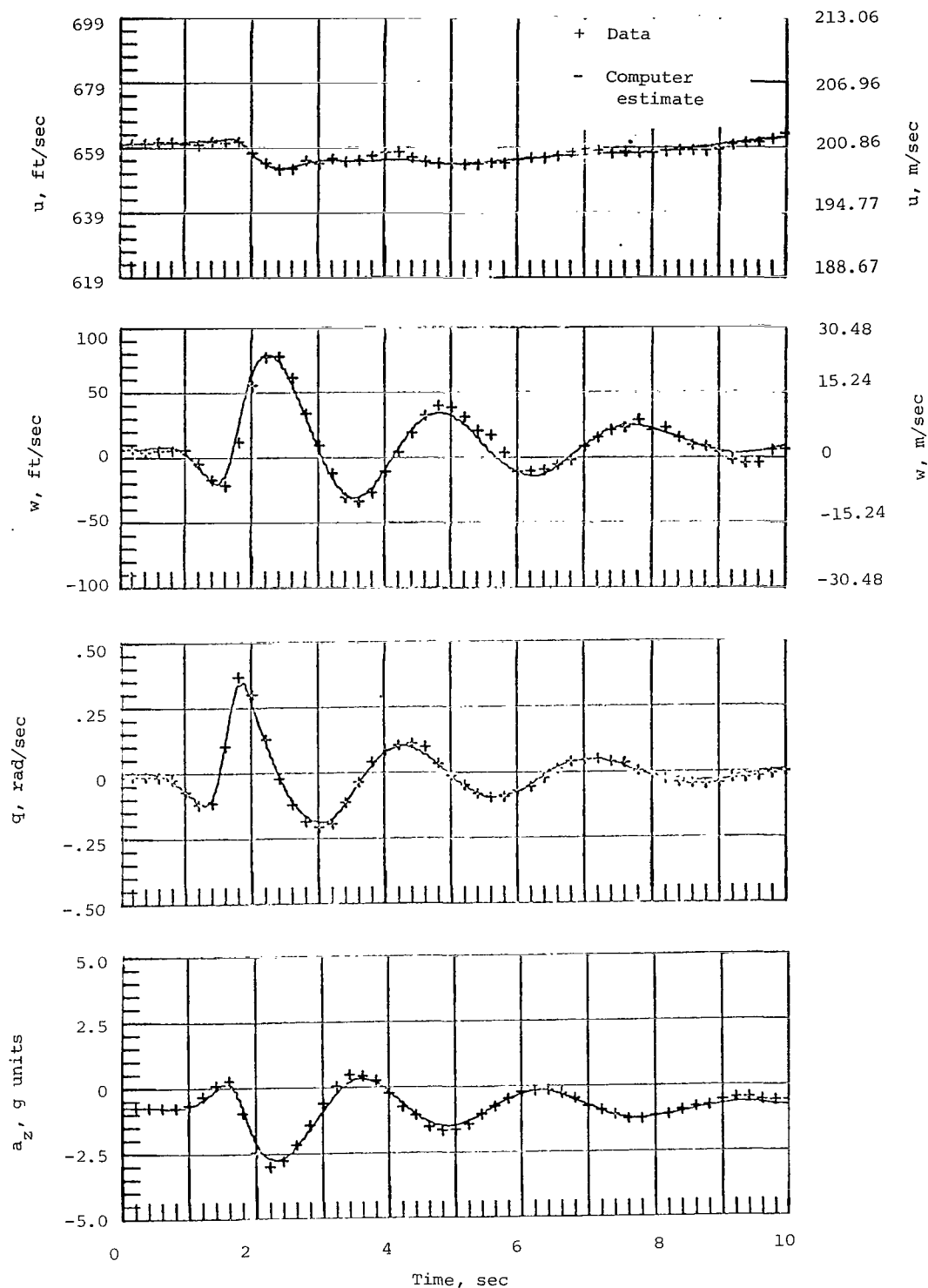Figure 10.- Continued.

(e) Test run 5.

Figure 10.- Concluded.
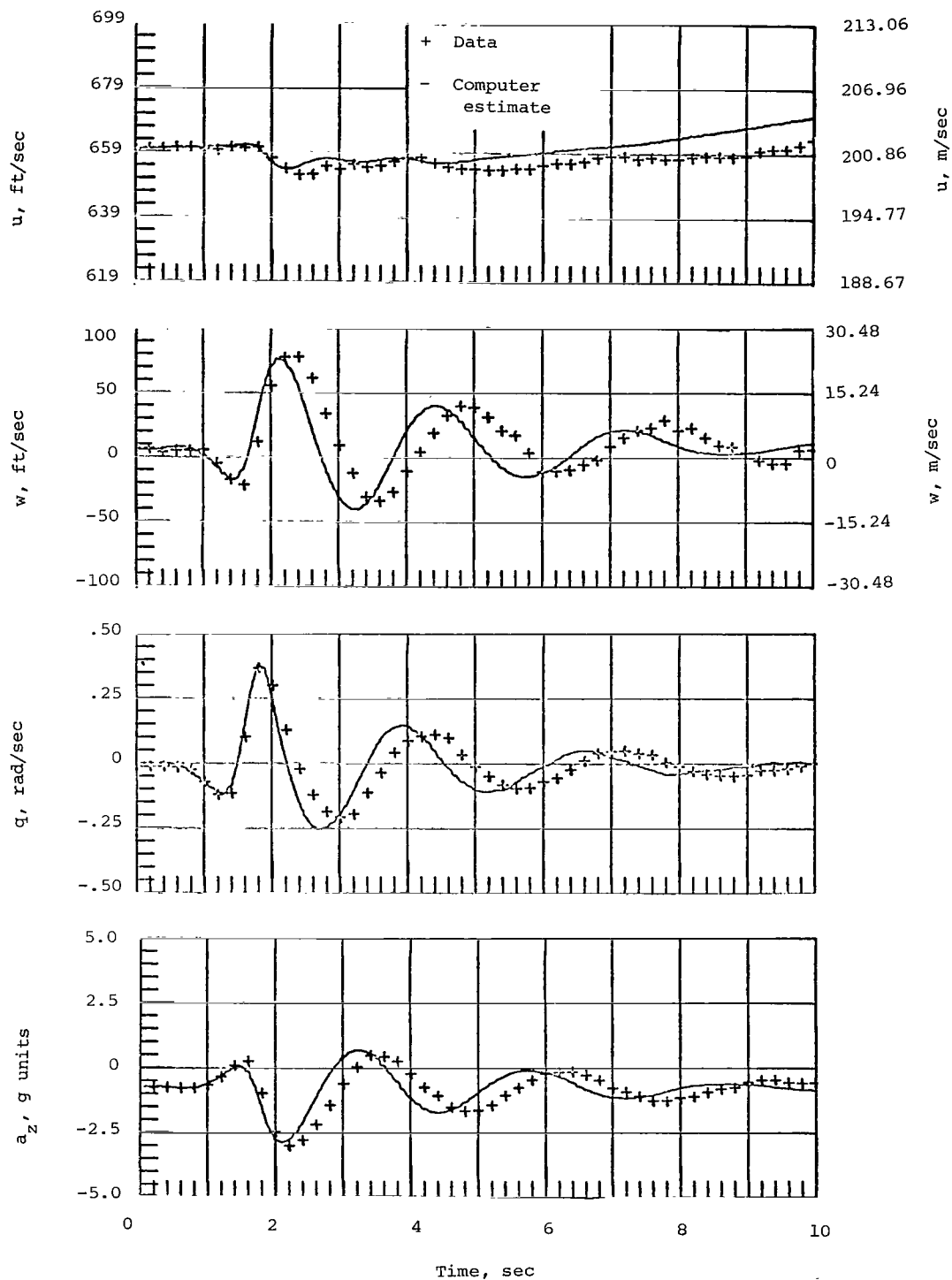
(a) Test run 1.

Figure 11.- Final model responses generated by using manufacturer's C_{m_α}, and other principal derivatives from extracted estimates.
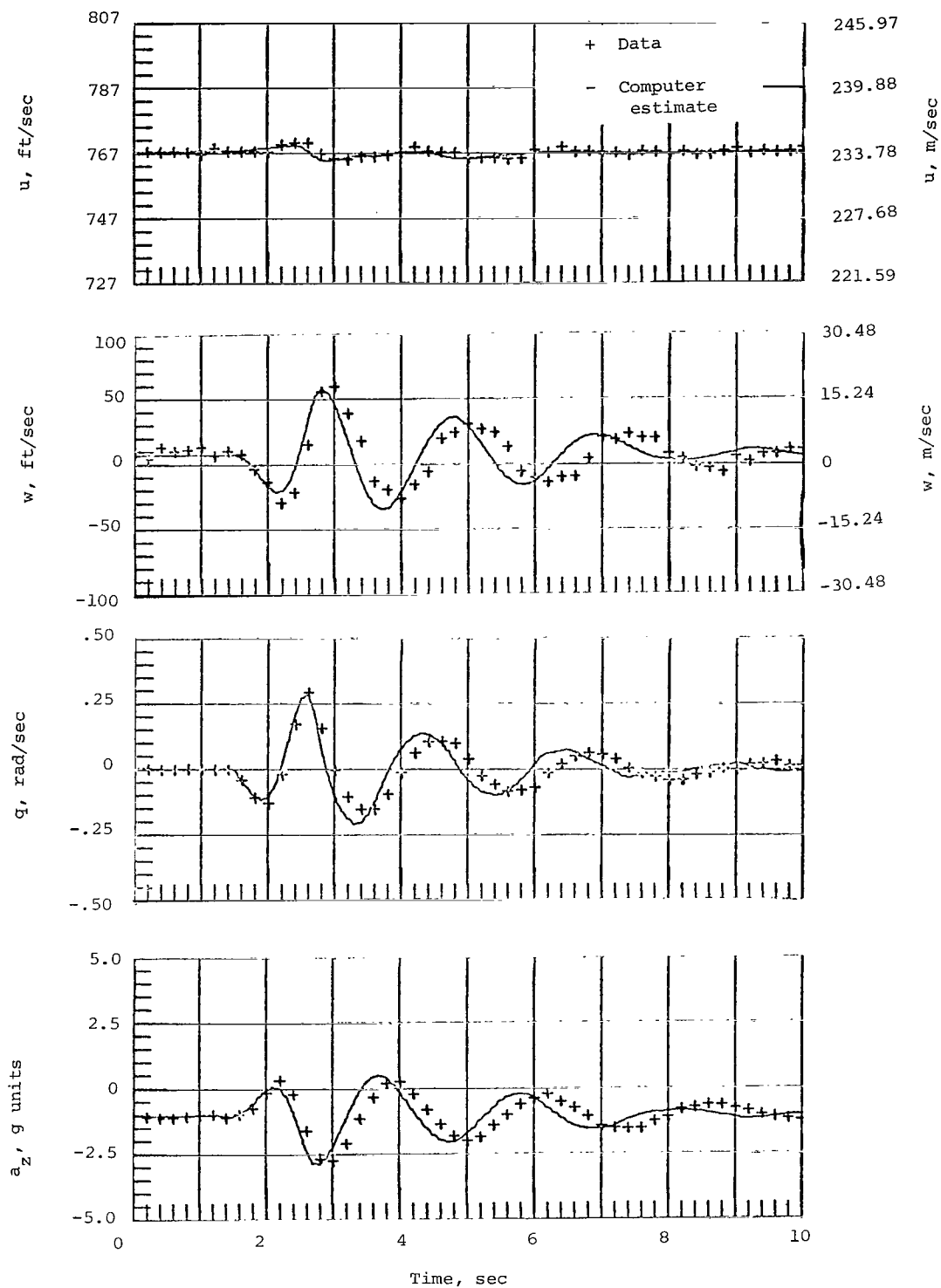
(b) Test run 2.

Figure 11.- Continued.

(c) Test run 3.

Figure 11.- Continued.

(d) Test run 4.

Figure 11.- Continued.

(e) Test run 5.

Figure 11.- Concluded.
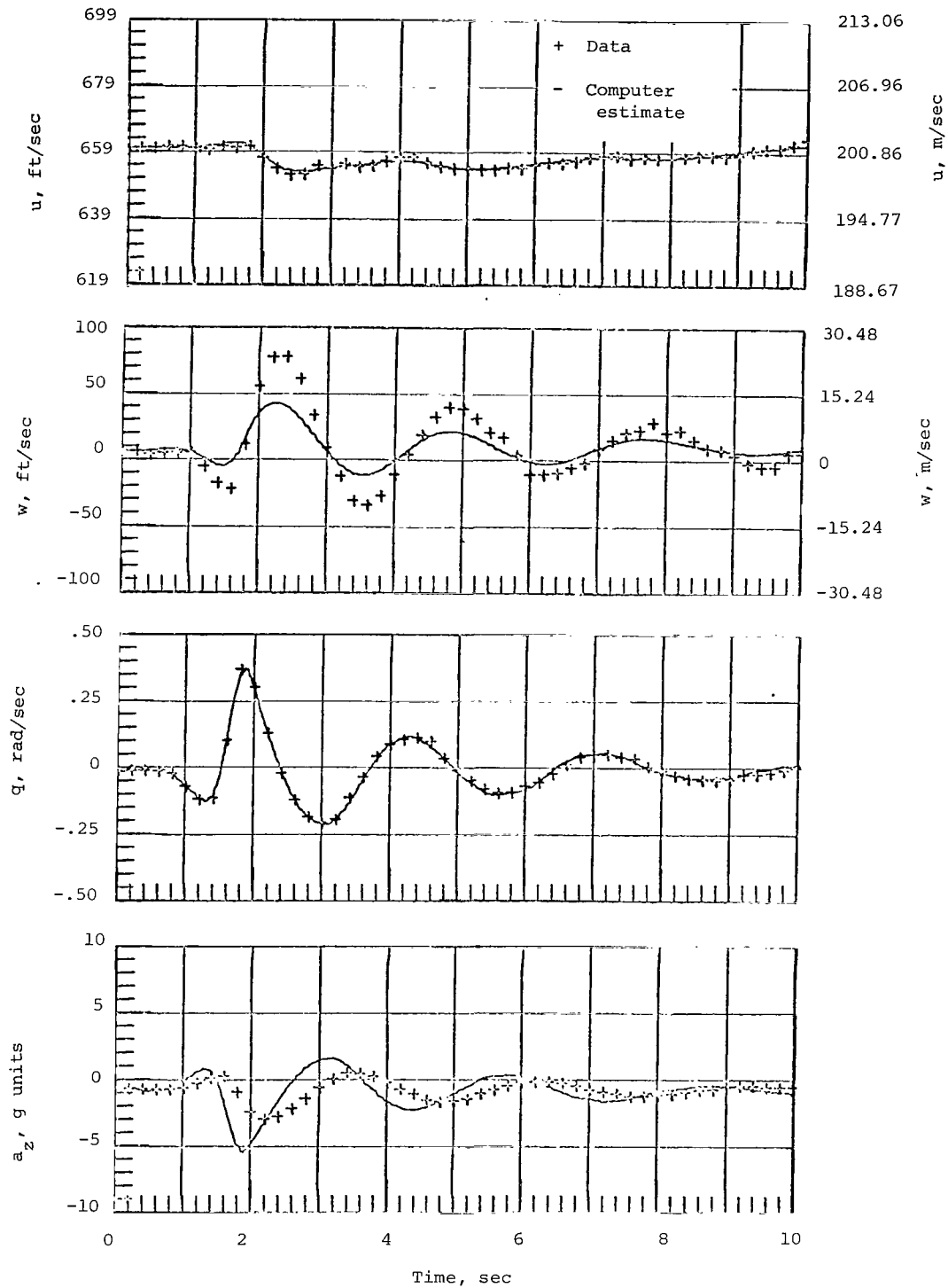
(a) Test run 1.

Figure 12.- Final model responses generated by using manufacturer's C_{m_α}, and other derivatives selected by algorithm.
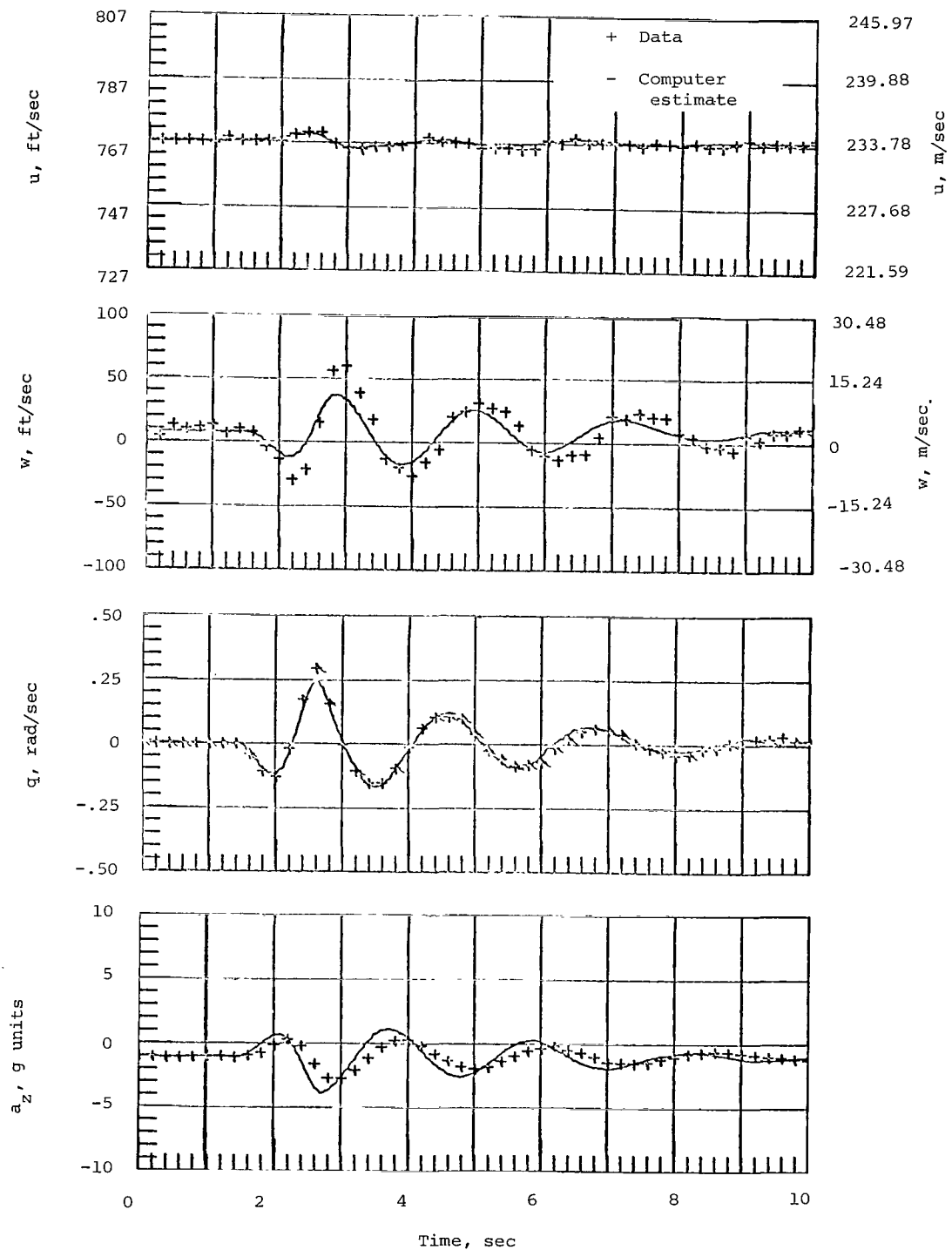
(b) Test run 2.

Figure 12.- Continued.
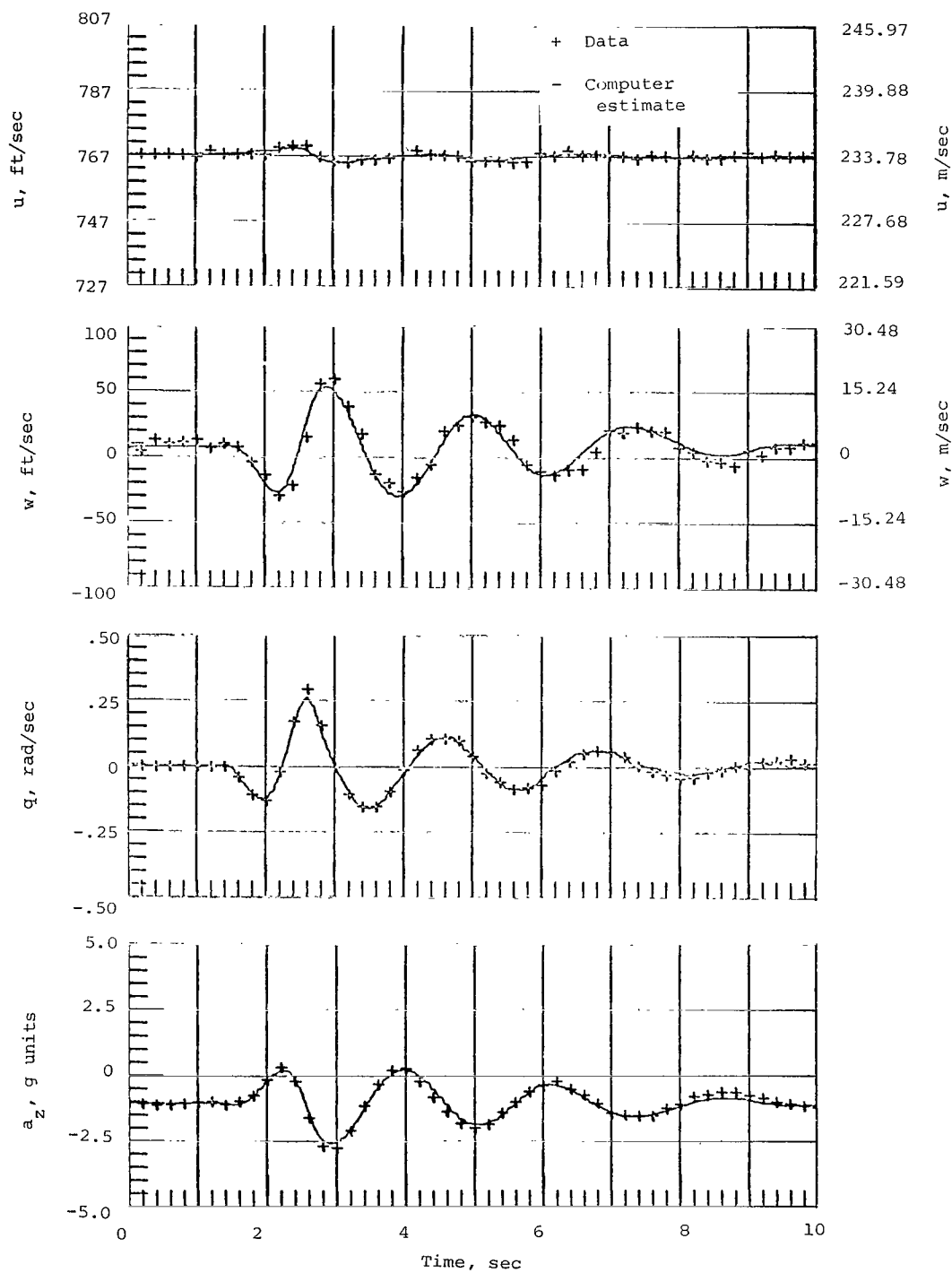
(c) Test run 3.

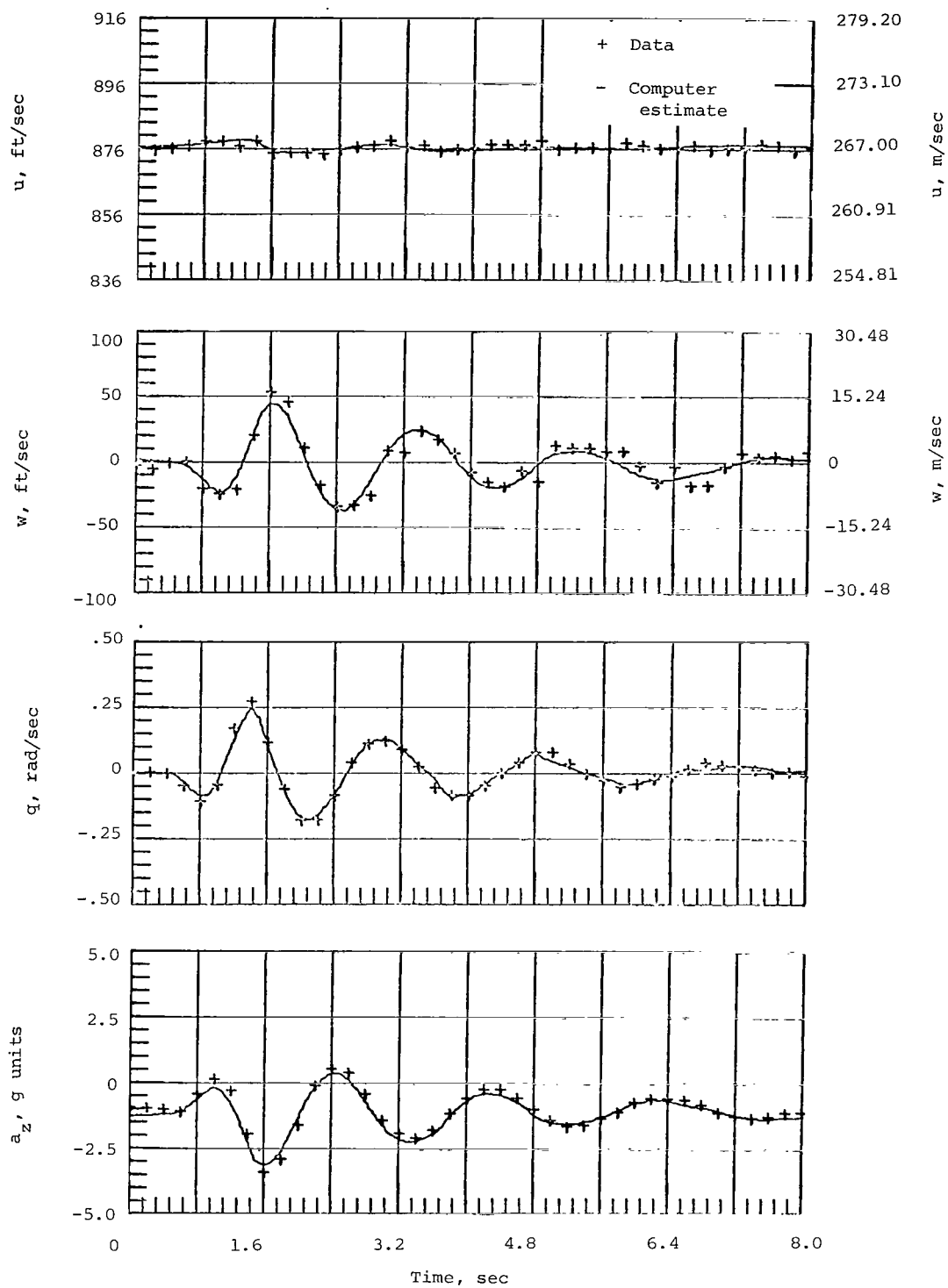Figure 12.- Continued.

(d) Test run 5.

Figure 12.- Concluded.

(a) Test run 1.

Figure 13.- Final model responses generated by using algorithm-selected C_{m_α}, and manufacturer's principal derivatives.
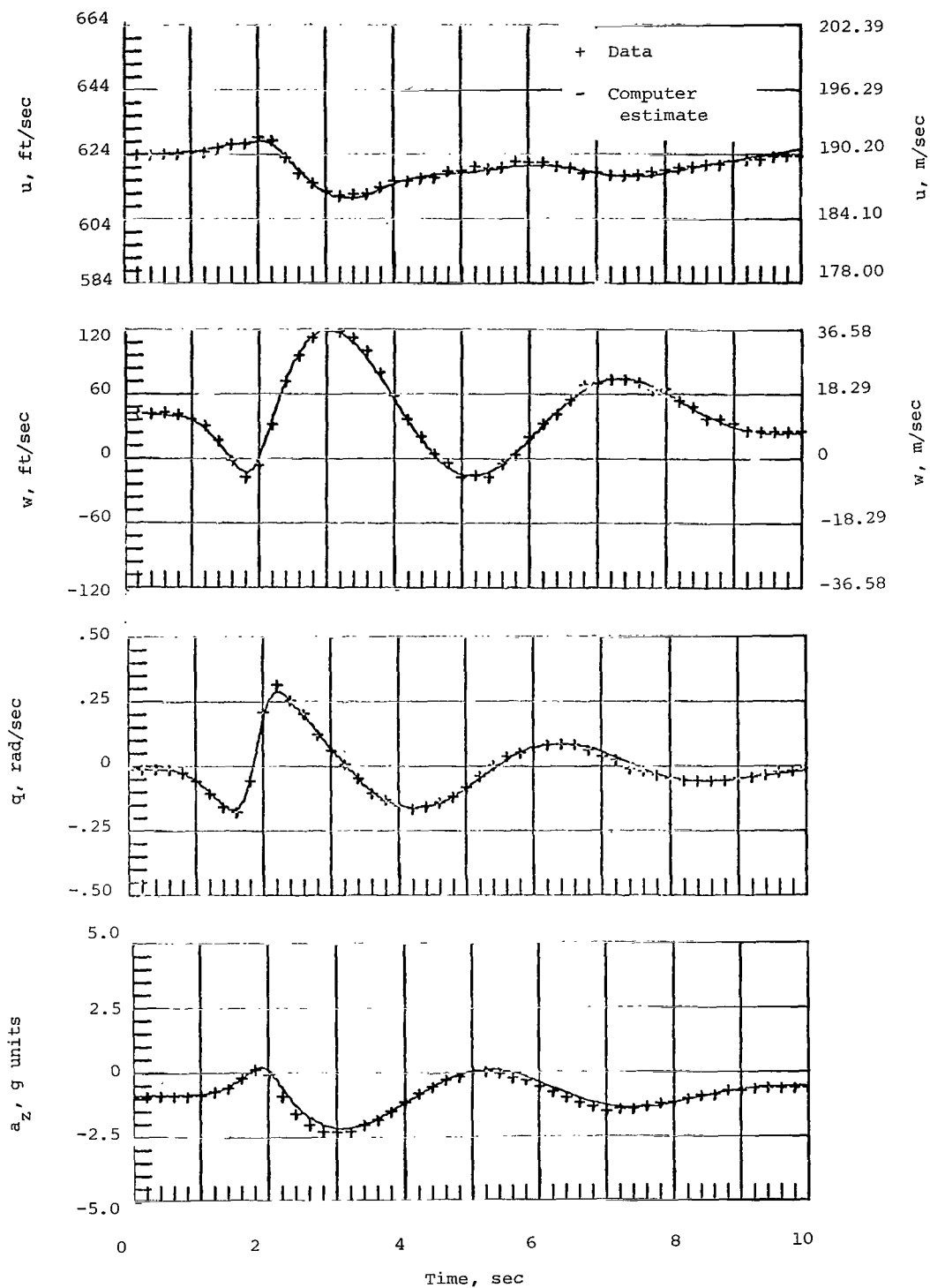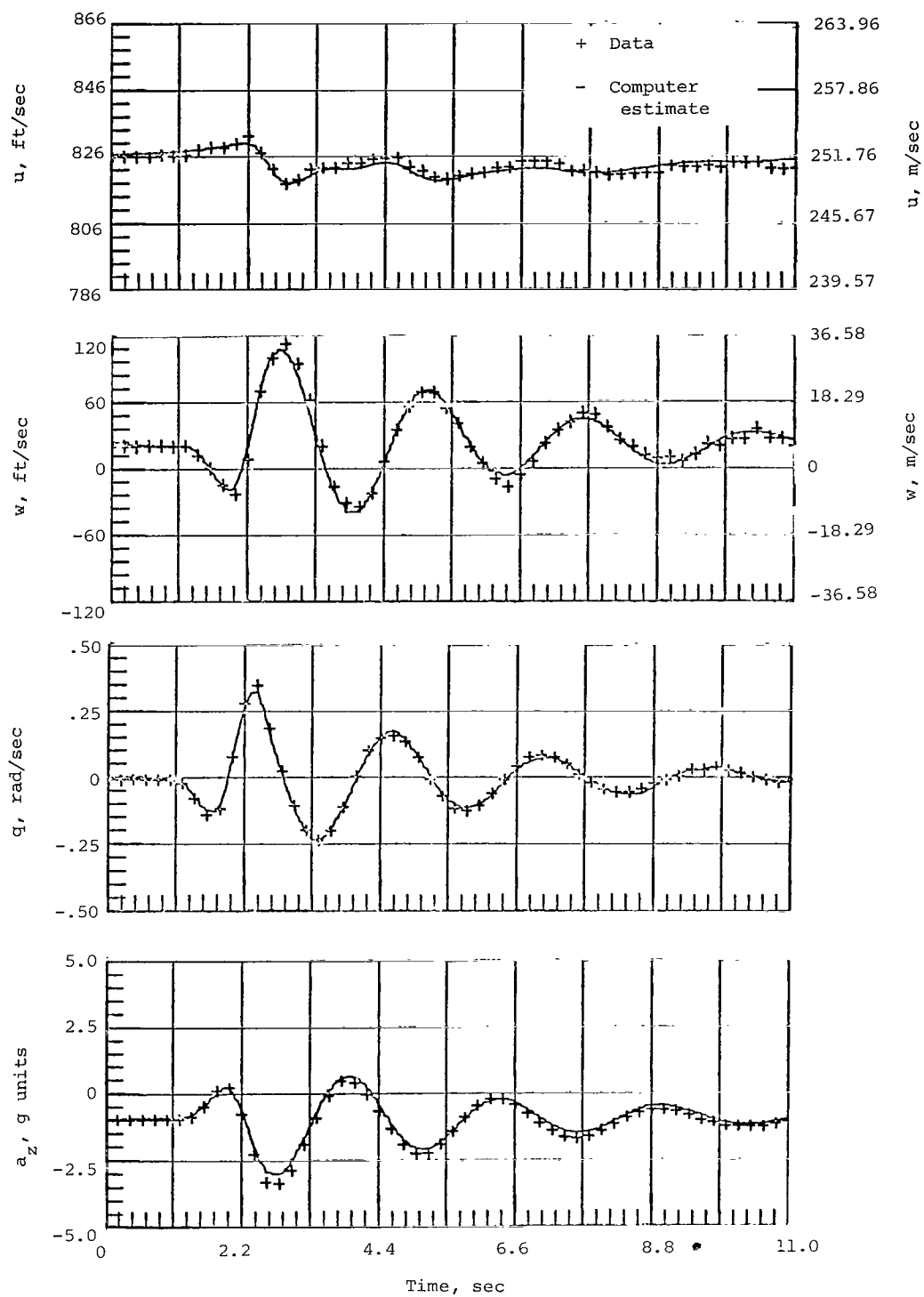
(b) Test run 2.

Figure 13.- Continued.

(c) Test run 3.

Figure 13.- Continued.

(d) Test run 4.

Figure 13.- Continued.

(e) Test run 5.

Figure 13.- Concluded.

△   Extracted from flight; 1524 m (5000 ft)

O   Extracted from flight; 6096 m (20000 ft)

───   Manufacturer's data; 1524 m (5000 ft)

- - -   Manufacturer's data; 6096 m (20000 ft)

▣   Algorithm extracted using fixed manufacturer's
    principal derivatives;   1524 m (5000 ft)

◇   Algorithm extracted using fixed manufacturer's
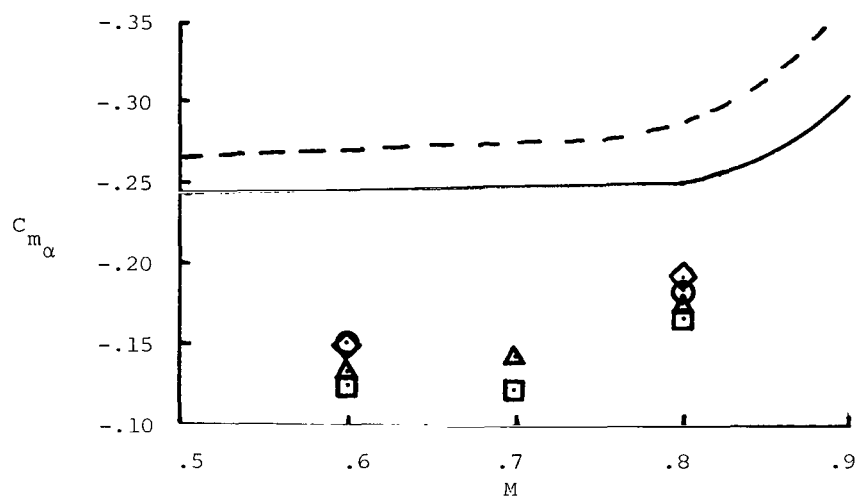   principal derivatives; 6096 m (20000 ft)

Figure 14.- Variation of C_{m_α} with Mach number.

"The aeronautical and space activities of the United States shall be
conducted so as to contribute . . . to the expansion of human knowl-
edge of phenomena in the atmosphere and space. The Administration
shall provide for the widest practicable and appropriate dissemination
of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and
technical information considered important,
complete, and a lasting contribution to existing
knowledge.

TECHNICAL NOTES: Information less broad
in scope but nevertheless of importance as a
contribution to existing knowledge.

TECHNICAL MEMORANDUMS:
Information receiving limited distribution
because of preliminary data, security classifica-
tion, or other reasons.

CONTRACTOR REPORTS: Scientific and
technical information generated under a NASA
contract or grant and considered an important
contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information
published in a foreign language considered
to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information
derived from or of value to NASA activities.
Publications include conference proceedings,
monographs, data compilations, handbooks,
sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION
PUBLICATIONS: Information on technology
used by NASA that may be of particular
interest in commercial and other non-aerospace
applications. Publications include Tech Briefs,
Technology Utilization Reports and
Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546